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Mechanical Design Report DARPA BOSS Program

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14. ABSTRACT

Several prototype zoom (variable magnification) lens systems were developed for use with short-wave infrared cameras as part of the DARPA BOSS program at NRL. These zoom systems relied on novel GRIN (GRadient INdex) lenses, which were used in two ways. The first approach deformed the lenses to alter system magnification, while the second approach moved the lenses relative to one another. This report describes the mechanical designs of both a prototype utilizing the first approach and a prototype utilizing the second approach. Also discussed are the performance of these mechanical systems after fabrication and testing; and possible improvement to be made in future prototypes. Included in the report are detailed mechanical drawings of the last prototype built for this program, which was also the best performing.

15. SUBJECT TERMS

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Zoom	Camera	Lens	Biologically inspired	Tunable

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Introduction

Through millions of years of evolution, nature has created a variety of unique optical systems that hold valuable lessons for engineers. The Defense Advanced Research Projects Agency (DARPA) Biologically-Inspired Optical Synthetic Systems (BOSS) program was a three year effort to develop optics inspired by nature. Five teams participated in the BOSS program, each adapting different lessons from nature to man-made systems. (1) The Naval Research Laboratory/Case Western Reserve University (NRL/CWRU) team developed novel GRIN (GRadient INdex) optics inspired by the human eye. This report covers work in the NRL Chemistry Division to design, build and test prototype BOSS systems.

Background

The path a ray of light takes through an ordinary isotropic lens changes direction at the interface between the lens and surrounding medium. The final path is dictated by the lens surface geometry and relative indices of refraction of the lens (n_L) and surrounding medium (n_S) as illustrated in figure 1. The angular change in direction at each interface is described by Snell's Law (equation 1), and the repeated application of Snell's Law to multiple rays can reveal a lens' imaging properties. (2) In GRIN lenses, the index of refraction varies through the bulk of the lens, such that a light ray continues to change direction beyond the surface. The ability to specify index of refraction gradients in the bulk of a lens provides additional degrees of freedom and a larger design space to the optical engineer. This allows greater system performance and/or improved aberration control within a given design space. In this program, the use of GRIN lenses yielded systems with fewer optical elements, lower mass and volume, and less spherical aberration.

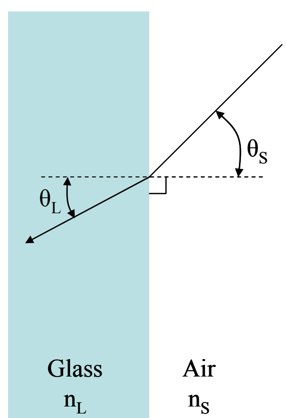

FIG 1 Illustration of Snell's Law at a planar interface with an isotropic (non-GRIN) material.

$$\frac{\sin\theta_L}{\sin\theta_S} = \frac{n_L}{n_S} = \Delta n \qquad [1]$$

Traditional GRIN lenses are fabricated by diffusing foreign materials into glass cylinders, which increases the index of refraction in a manner dictated by the diffusion coefficient. The resulting index of refraction distribution is symmetric about the cylinder axis and the profile is generally parabolic. This technique has yielded successful products but has several severe limitations. Among these are the limits on lens size, lens shape, and complexity of index of refraction profile. It is also limited to glasses, which in most cases are heavy when compared to polymer lenses.

A new technique for GRIN lens fabrication was developed collaboratively by CWRU and the NRL Optical Sciences Division. (3) This technique eliminates the prior restrictions by enabling the designer to generate virtually any index of refraction profile in large or small polymer lenses. The fabrication process begins with two polymers of different indices of refraction, which are co-extruded to produce a sheet composed of thin alternating layers. By varying the relative thicknesses of the layers, the average index of refraction of the entire sheet can be tuned to any point between the indices of refraction of the constituent polymers.

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When the layers are made thin enough (less than λ/10), light rays behave as if the sheet were monolithic. Stacking, fusing, bending and polishing these sheets can result in a variety of index of refraction distributions. More importantly, these distributions can be specified beforehand and then accurately fabricated, so that optical designers can use them as an additional design variable in complex, multi-element systems.

Goals

Program goals for the NRL/CWRU team included:

1. Expand the CWRU GRIN lens fabrication technique to larger lenses, more complicated index of refraction profiles and larger overall Δn.
2. Improve the quality of lenses produced at CWRU
3. Understand how these GRIN lenses work through analysis and modeling
4. Develop GRIN lens design tools and learn how to design systems incorporating them
5. Design and build prototype zoom systems utilizing GRIN optics to demonstrate the technology
6. Fly prototype systems on Unmanned Air Vehicles (UAVs) to demonstrate GRIN technology and guide development by having a specific application defined.

NRL code 6110 made contributions to goals four and five and took complete responsibility for goal six. Contributions to goal five included complete mechanical and electromechanical designs of prototype zoom systems. For goal six, code 6110 integrated prototype systems into UAVs and conducted flight tests.

Specifications and Approach

A UAV surveillance camera was chosen as the prospective application for the BOSS prototypes. UAVs have stringent mass and volume limits that challenge existing optical zoom technology, and were expected to highlight the advantages of GRIN lenses. The planned test platform was the *Dragon Eye* UAV. Based on discussion with *Dragon Eye* operators, the following specifications were chosen:

TABLE I. Zoom system for UAV specifications.

Number	Specification	Value
1	Zoom level	2-3X
2	Zoomed-in horizontal field-of-view (HFOV)	20°
3	Mass limit (including actuation, not camera)	200 g
4	Largest dimension (likely along optical axis)	10 cm
5	Wavelengths of operation	0.9-1.7µm Short-Wave Infrared (SWIR)

Specifications #1 and #2 were based on *Dragon Eye* operator input; #3 and #4 were based on *Dragon Eye* payload limits. The decision to use SWIR rather than visible light in specification #5 was the result of two factors. First, there is a great deal of interest in starless, moonless night time imaging and the SWIR band can provide this capability by relying on the "night glow" phenomenon[1]. Second, the longer wavelengths of SWIR light allowed thicker layers in the extruded polymer sheets due to the λ/4 limit, and thus fabrication tolerances could be less stringent. The Goodrich-Sensors Unlimited SU-320us 1.7RT SWIR microcamera (figure 2) was chosen because it was designed for use on UAVs and in 2004 it was the smallest and lightest SWIR camera on the market. While not sensitive enough to image using the night glow, it could image in light environments from noon to dusk. Later versions were expected to have improved sensitivity in the same package and could be used as direct replacements. It also offered an industry standard C-mount interface for optics, which provided good access to the focal plane array (FPA). Finally, it had both analog and digital (CameraLink) video outputs. The analog signal could be used on a UAV, while the CameraLink signal could be used on the ground for sophisticated image quality analysis.

[1] The night glow is energy in SWIR wavelengths (~1.5µm) radiated by the atmosphere at night. It comes from a variety of sources including sunlight (stored chemically from the daytime) and cosmic rays.

FIG 2 Sensors Unlimited SU-320us 1.7RT SWIR microcamera

In order to achieve the goals listed above, the mechanical/electromechanical design and testing carried out by NRL code 6110 were guided by the specifications in Table I and by the optical designers in NRL code 5600. As the project progressed, three GRIN-based zoom lens concepts were suggested by the optical designers and then investigated by building and testing prototypes. These concepts (in chronological order) were:

1. Deform semi-rigid polymer GRIN lenses by applying mechanical force to them. Rely on GRIN to correct for aberrations introduced by the deformation.
2. Seal rigid polymer GRIN lenses in an elastomeric gel-filled envelope. Apply mechanical force to drive the gel from one section to another and deform the envelope. Rely on GRIN to correct for aberrations introduced by the deformation.
3. Move rigid polymer GRIN lenses along the optical axis in the same way traditional optical systems work, but take advantage of GRIN properties for better performance: fewer elements, lower mass and volume, and clearer images.

The first concept failed when testing revealed that large forces and displacements were required to produce noticeable changes in image magnification. No small and lightweight actuation system could be found to supply the required force and displacement. Concept #1 ended in the laboratory proof-of-concept stage, whereas prototypes were built utilizing concepts #2 and #3. The two main design sections of the report refer to those prototypes.

Design Process

Group Interaction

The design process was iterative, with the three groups (see figure 3) working in parallel to converge on a final design. It began with the Optical Sciences group, which would produce an optical design specifying the number of lenses and the geometry, properties and positions of each lens. CWRU would take this information and begin fabricating lenses, while code 6110 would begin the mechanical design. Once a set of lenses had been fabricated, Optical Sciences would evaluate them and either adjust the design to account for newly identified fabrication limits, or suggest improvements for the next iteration. Code 6110 updated the tentative mechanical design each time the optics changed. When the final optical design emerged, code 6110 would finalize the mechanical design and find a shop to fabricate the necessary parts, while CWRU fabricated the final lenses. When both the optics and mechanical components were complete, they were assembled and tested. In some cases this testing lead to further design changes and the fabrication of modified parts. In other cases it spawned a whole new design based on what had been learned.

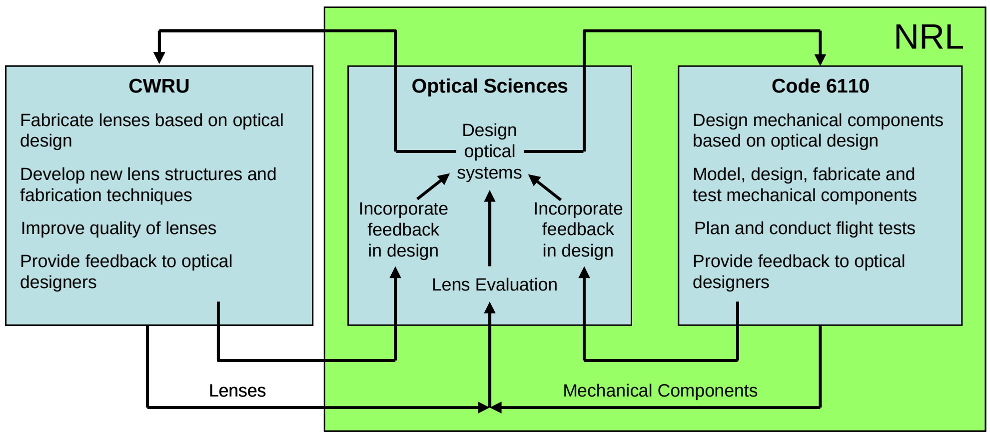


FIG 3 Design process and interaction between groups

Methods

The optics design process began following camera selection, so that the system could be optimized for the dimensions and pixel pitch of the chosen FPA. After writing custom codes to accommodate GRIN profiles, the optical designers used the ZEMAX software package to design and model the optics. Each design iteration yielded a set of .iges files[2] describing the size, shape and relative positions of the lenses. In most cases four files were provided to the mechanical designer: two describing lens position extrema and two describing intermediate positions. This was generally sufficient to specify how the mechanical components must move through the zooming process and avoid part collisions. In some cases the lens motions were more complex and the files were accompanied by a table listing lens spacing for various zoom states. These .iges files were imported into the SolidWorks CAD/CAE package so that mating mechanical components could be designed accurately and referenced directly to the optical model.

Choosing an actuation method was the first step in the mechanical design process. An in-depth study of available actuators was undertaken and published as an NRL report. (4) The anticipated force-displacement curve for each prototype design was compared to the study results in order to select the most appropriate actuator. Once the actuator had been chosen and a basic plan for linking the actuator to moving elements had been established, mounts were designed for lenses and apertures. Then a housing was designed to accommodate the mounts. The actuation system was added to the housing and linked to the parts that would translate. A mechanical interface with the camera was designed. Finally, appropriate tolerances were applied to critical parts and surface finishes were chosen.

[2] .iges files are an industry standard for storing and conveying 3D solid design data.

Designs were tested extensively in SolidWorks before fabrication. Light rays included in the .iges file were used to ensure that at no point in the zooming process would any of the mounts cause vignetting problems. Parts were driven in the solid model as they would in operation to ensure that none would collide. Simple finite element analysis (FEA) was performed on key load bearing parts to evaluate and adjust the design factor of safety.

As the program progressed, it became increasingly clear to both the optical and mechanical designers how important proper specification of prototype characteristics and tolerancing were to the success of each device. As a result, each device had more extensive specifications and tighter tolerances than the previous one. This trend culminated with the final device (prototype 3.4) which had specifications for system mass and length; tolerances for lens spacing, tilt, and diameter; tolerances for lens to lens concentricity and lens perimeter to focus concentricity; and temperature limits.

Tunable Zoom GRIN System (Prototype 2.0) – Approach #2

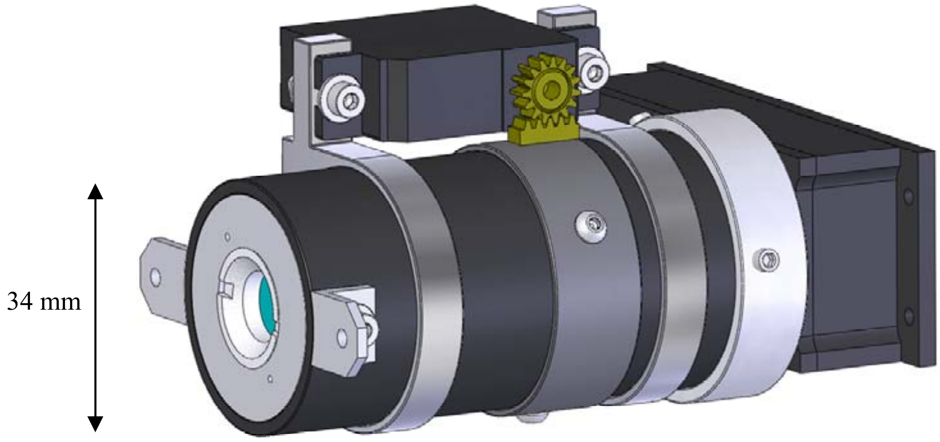


FIG 4 SolidWorks rendering of prototype 2.0 with SWIR Camera

The completed prototype is illustrated in figure 4. The optical design consists of five elements (see Table II, figure 5), three of which are fixed focal length polymer GRINs and two are "tunable" GRINs. The tunable GRIN lenses consist of a solid polymer GRIN lens and reservoir of partially cross linked silicone, enclosed by an elastomeric shell. These were designed to be compressed at the perimeter in a direction parallel to the optical axis. When compressed, a fraction of the silicone is forced toward the center, causing it to bulge. The bulge reduces the radius of curvature (increases optical power) of one refracting surface and thereby reduces the focal length of the lens. When the compressive force is removed and the lens is allowed to relax, the focal length increases. The internal GRIN lenses are included to add optical power and correct for aberrations introduced by the deformed shell surface. In a zoom configuration, they are deformed concurrently with one lens allowed to relax by the same amount the other is compressed. This way the lenses can remain in fixed locations while the location of the focus between them (and hence system magnification) shifts (see figure 6). The silicone filled tunable lens concept originated at CWRU and the concept for the shifting focus optical zoom was conceived by James Shirk in NRL Optical Sciences.

TABLE II. Optical elements in prototype 2.0

Element	Geometry	Type	Purpose
1	Plano-concave	Polymer GRIN	Gather light from a wide field of view
2	Plano-convex	Polymer GRIN	Direct light into first tunable lens
3	Biconvex	Tunable GRIN	Change image magnification
4	Biconvex	Tunable GRIN	Change image magnification
5	Plano-convex	Polymer GRIN	Focus image onto focal plane

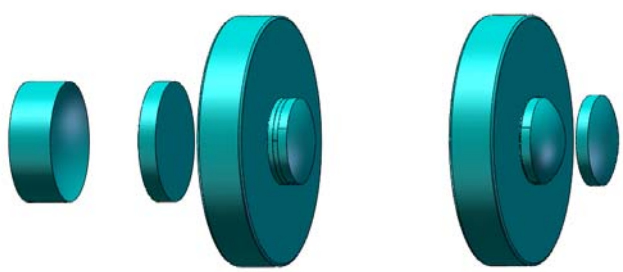


FIG 5 Rendering of prototype 2.0 lenses.

In laboratory testing the tunable lenses were oriented "back to back" and retained by fixed Delrin annuli at either end. A cylindrical tube between them (the plunger) could shift position to compress one lens and allow the other to relax. This arrangement was adopted for prototype 2.0 because it was well characterized and worked in laboratory pre-prototypes.

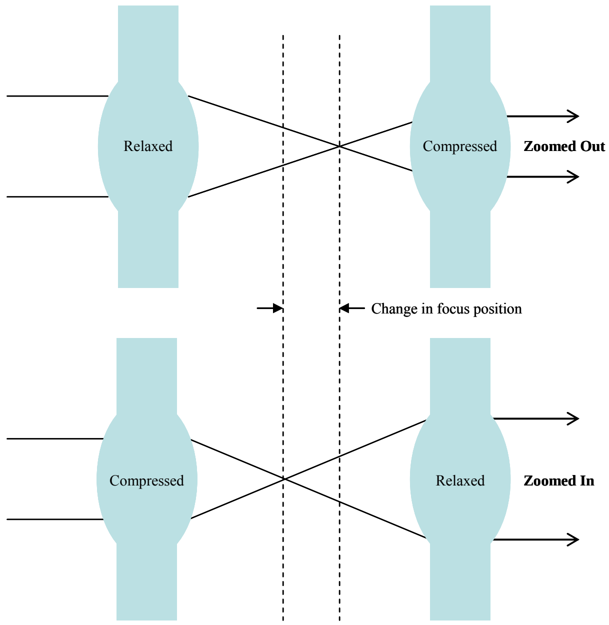


FIG 6 Operation of tunable lenses in prototype 2.0 when zooming in and out

Mechanical Design Requirements

The requirements for this design are listed in table III.

TABLE III. Prototype 2.0 mechanical design requirements

Characteristic	Value
Minimum tunable lens compression	1.2 mm
Maximum mass (including actuation)	200 g
Maximum length (including camera)	10 cm
Fixed lens position accuracy	None specified
Fixed lens angular accuracy	None specified
Lens concentricity	None specified
Temperature range	None specified
Minimum BFL adjustment	±2.0 mm from design focus

Component Design

All components are either inside of or attached to a cylindrical tube called the housing (see figure 7). The ends of the housing are internally threaded to accommodate mounts holding fixed focal length GRIN lenses. Between the threaded sections is a smooth bore of smaller diameter in which the plunger resides. The smooth bore allows the plunger to slide freely along the optical axis when driven by the servo (held externally to the housing) through three slots at 120° increments around the optical axis. There are three threaded holes at 120° increments around the optical axis at one end of the housing for screws mounting the camera adapter. There are two L-shaped brackets that bolt onto the front sides of the housing. In the UAV these rest against the inside of the nose wall and provide a place to secure the zoom assembly to the nose.

The first two lenses are housed in a cylindrical mount having both external and internal threads (see figures 8a and 9a). Lens 2 rests on a shelf in the mount and is held in place by a threaded spacer, which when screwed in following lens 2 establishes the correct distance between lenses 1 and 2. Lens 1 rests on a shelf in the spacer and is held in place by a threaded retaining ring. There are notches in the front surfaces of the spacer and retaining ring so they can be screwed in easily with a spanner wrench. The two 1mm diameter holes in the mount allow a similar spanner wrench to be used to screw the entire mount into the housing. The retaining ring has a 45° chamfer to prevent vignetting. The reduced outer diameter at one end of the mount simply minimizes the mass.

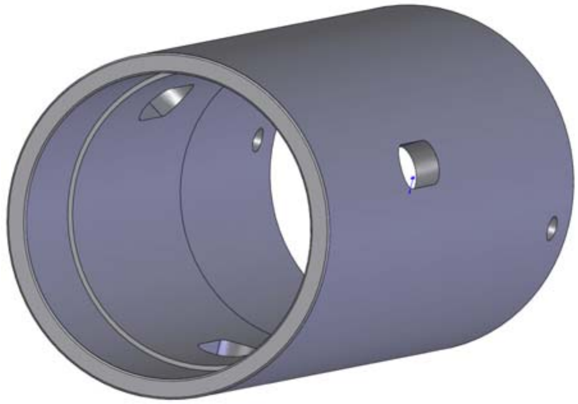
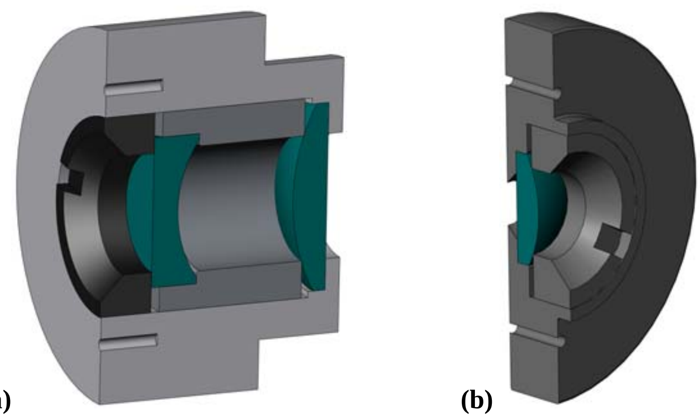


FIG 7 Prototype 2.0 housing to which all other components are attached.

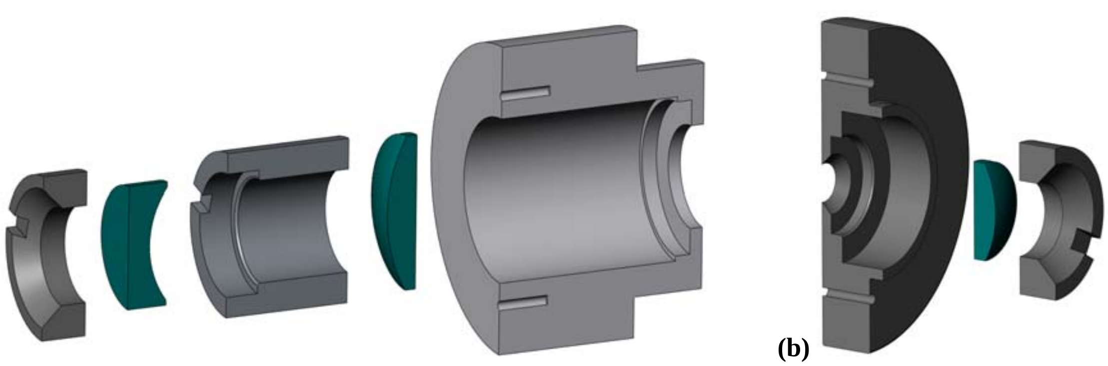
The mount for lens 5 (see figures 8b and 9b) is also a cylinder with external and internal threads. The lens rests on a shelf and a retaining ring is screwed in from behind to secure it. This retaining ring has a 45° chamfer to prevent vignetting. The aperture leading from lens 4 in the optical train is chamfered to create a 3.50 mm diameter hard stop specified in the optical design.

The housing is hard coat anodized black to reduce internal reflections. The fixtures, spacer and retaining rings are made of black Delrin because it is lightweight, easily machinable, has low reflectivity when the surface is treated properly, and is dimensionally stable in varying temperature and humidity environments.



(a) **(b)**

FIG 8 Assembled cross sections of the mounts for lenses 1 & 2 (a) and lens 5 (b) in prototype 2.0.



(a) **(b)**

FIG 9 Exploded views of the mounts for lenses 1 & 2 (a) and lens 5 (b) in prototype 2.0.

The tunable lens assembly consists of all components needed to hold the tunable lenses in place and compress them (see figure 10). When force is applied to the rack (part *k*) by the servo, part *j* is forced to move along the optical axis. Three screws (part *h*) connect part *j* to part *g* through the slots in the housing. Parts *f* and *g* both have smooth outer surfaces so they slide easily in the housing bore. Part *g* does not bind because the width of part *j* prevents it from losing alignment with the housing. Part *e* compresses the lens when it is acted upon by parts *f* and *g*. Part *d* is cemented to the tunable lens perimeter before the zoom system is assembled. The ring keeps the soft tunable lens centered on the optical axis, but has a smooth outer diameter so that it can slide along the optical axis in the housing bore. This prevents binding when the lens is compressed, which could otherwise introduce tilt in the lens surface. Part *b* is the solid stop against which lens 3 (part *c*) is compressed. The rounded shape of part *b* is designed to compress the lens without deforming the envelope beyond its yield stress and minimize hysteresis. Part *b* has two 1mm diameter holes so that a spanner wrench can be used to screw it into the assembly housing. Part *a* determines the distance between lenses 2 and 3 and links the first fixed focal length lens mount to part *b* so that neither will unscrew. Delrin bearings (part *i*) on the screws perform three functions: minimize friction on the slots, keep the screws centered in the slots and set the gap between the slider outer diameter and slider ring inside diameter. Control of this gap is critical because it determines the friction force between parts *j*, *g* and the housing. This in turn determines the friction force encountered by the servo when compressing the tunable lenses. The parts associated with lens 4 (part *n*) work the same was as those for lens 3, but in this case part *o* is held in place by the mount for lens 5. The rack is attached to the slider ring with epoxy.

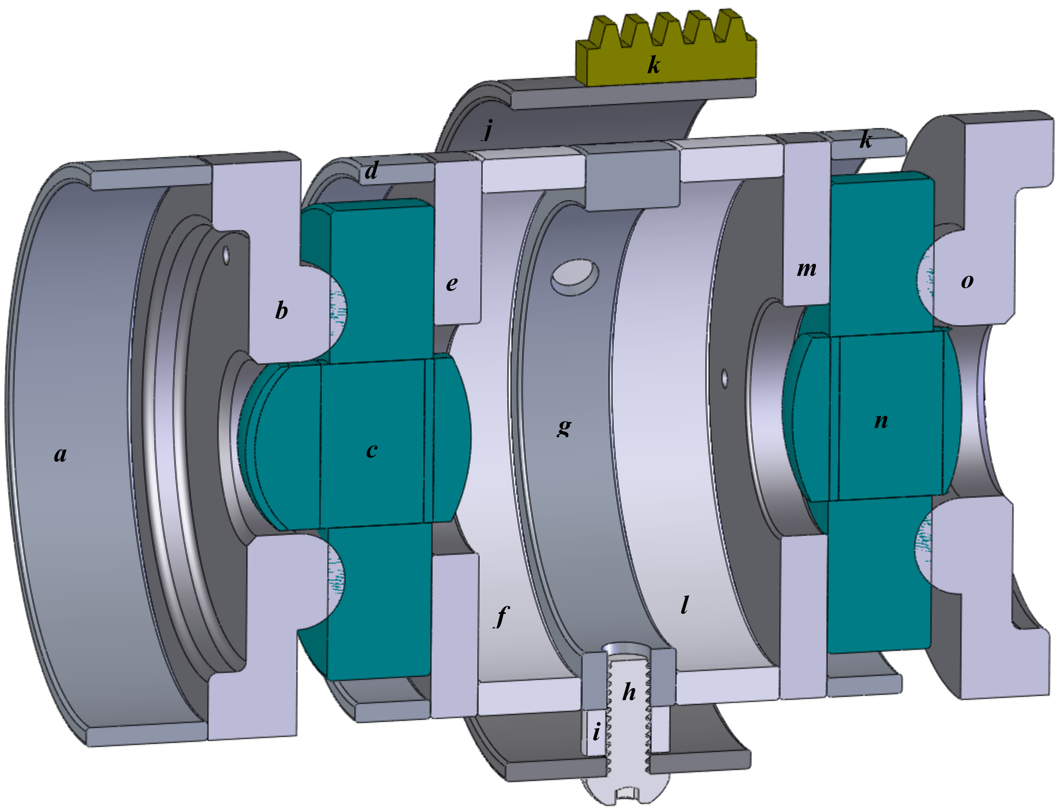


FIG 10 Tunable GRIN lens assembly.

Parts *b*, *e*, *f*, *i*, *l*, *m* and *o* are made of Delrin for the same reasons it was used for the fixed focal length lens mounts. Additional reasons include the low coefficient of friction between Delrin and aluminum and the lower probability of damage to the tunable lenses by sharp edges on plastic parts. Parts *a*, *d*, *g* and *k* are 6061-T6 aluminum hard coat anodized black. The rack is brass.

The servo is held in place by two rings that slip over the outside of the housing, which are then secured by set screws that bear against the housing outer surface. The servo is fixed to ring posts using socket head cap screws that pass through slots in the posts as illustrated in figure 11. Slots were chosen so that the pinion/rack pressure angle could be adjusted and backlash reduced to improve slider position accuracy.

FIG 11 Servo assembly shown from two perspectives.

The camera interface (figure 12) is a sleeve that threads into the C-mount threaded hole in the camera housing and slips over the outside of the housing. The camera interface is secured to the housing by three set screws set at 120° intervals about the optical axis. The camera adapter provides focus adjustment for the zoom assembly because its position on the housing can be adjusted and then fixed by tightening the set screws.

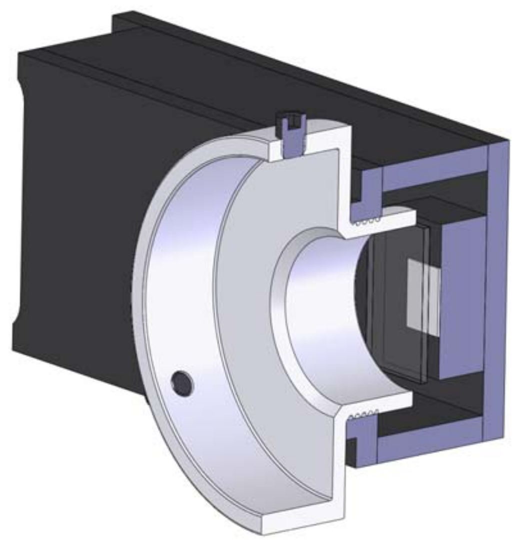


FIG 12 Cross section view of SWIR camera and camera adapter.

Actuator Selection

The large tunable lens displacement specified by the optical design ruled out most actuation technologies in the study (4); servo and stepper motors were the only two that can provide sufficient displacement. Because this prototype was to be tested on a UAV and model aircraft servos would greatly simplify the electronics integration process, they were evaluated first. If a strong enough model aircraft servo could be found, it would be used and the more complex stepper motors would not be considered. The highest torque "mini" servo available was the Futaba S3002 (see table IV). Lens compression force data were used to determine whether or not this servo would be sufficient, but first a method of driving the plunger with a servo had to be chosen.

TABLE IV. Futaba S3002 servo characteristics

Characteristic	Value
Stall Torque @ 6.0V	45.13 N-cm
Operating Angle	±45°
Bearing Type	Ball Bearing
Gear Material	Brass
Mass	37.2 g
Dimensions	30 x 15 x 30 mm

A linkage, screw/nut or pinion/rack are all common methods of converting angular displacements into linear displacements. The linkage was eliminated because this application requires a system that can apply equal force in two opposing directions. A linkage satisfying this requirement would have been the most complicated of the three methods. The screw thread pitch and diameter necessary to produce the required 1.2 mm displacement with ±45° servo rotation suggested that an unreasonable screw pitch-diameter combination would be necessary, so the pinion/rack was chosen. A variety of gears designed to interface with the servo output shaft splines were available, but the smallest (and hence lightest) gear that would provide sufficient displacement with the available angular displacement was an 8.9 mm (0.35 in) diameter 48 pitch brass spur gear. A compatible rack was also purchased.

Testing yielded a lens compression force-displacement curve (see figure 13) that could be used to compute the required servo torque. The equivalent spring constant for the lens was found to be k_{lens}= 16.0 N/mm. The lenses in this prototype can be modeled as two springs fixed at one end and linked in the center (figure 14). The servo applies force to the plunger between the springs. Analytically it can be shown that the maximum force required from the servo will be the maximum force required to compress a single lens, if both lenses are 50% compressed at equilibrium. This is true for the lens-plunger system.

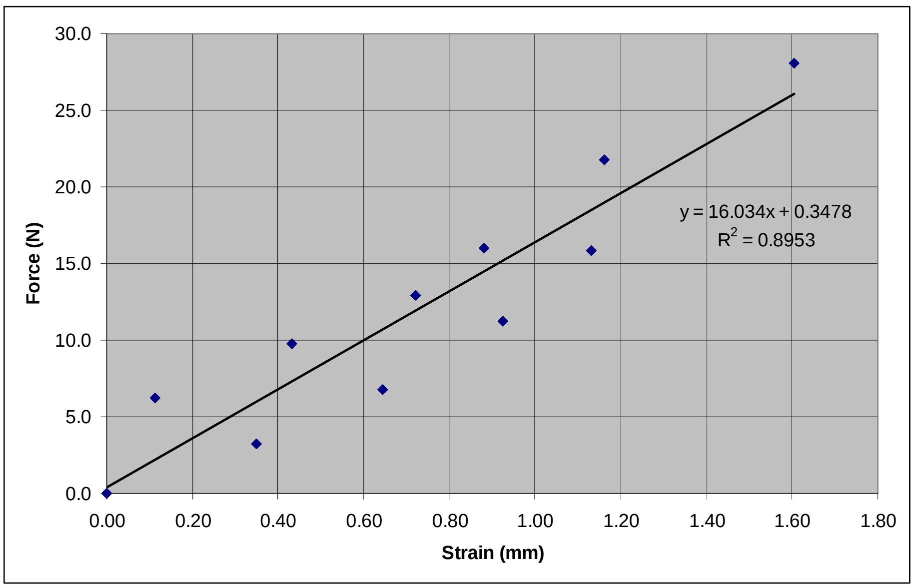


FIG 13 Force-Displacement curve for tunable GRIN lenses from CWRU. (5)

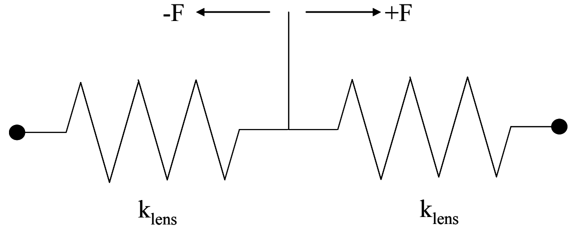


FIG 14 Model of two partially compressed tunable lenses with plunger.

Given the displacement required for sufficient lens compression was x_{lens} = 1.2 mm, the necessary lens compression force was calculated using Hooke's Law (equation 2) and found to be F_{req} = 19.2 N.

$$F_{req} = k_{lens} x_{lens} \quad [2]$$

In order to apply this force to the plunger, the servo must supply τ_{req} = 85.44 N·m to the pinion, as calculated by equation 3.

$$\tau_{req} = \frac{1}{2} F_{req} D_{gear} \quad [3]$$

Comparing the required torque to the maximum torque available from the Futaba S3002 yields a safety margin of 5.2, which is quite large. Servos with a lower maximum torque specification were available, but they offered only marginal reductions in servo mass. The S3002 was therefore chosen because there was no advantage to using a less torque dense servo, and the large safety margin provided by the S3002 was expected to easily accommodate the assumptions in this calculation. These assumptions included Hooke's Law behavior in the tunable lenses and a perfectly efficient drive train.

Fabrication and Assembly

Parts were fabricated by Edmunds Engineering (Temple Hills, MD) using computer numerical control (CNC) equipment reading directly from SolidWorks .step files. An outside finishing shop applied the anodization.

Prototype 2.0 was assembled by first inserting part *g* into the housing. Then the bearings were set in the housing slots. The part *j* was slid over the outside of the assembly housing and the three screws were inserted to connect part *j* to part *g* through the bearings. The housing was rotated so that it was oriented vertically and the parts *f* and *e* were dropped in. Lens 3 was inserted (GRIN side down) until it was in contact with part *e*. Part *b* is screwed in using a spanner wrench until it contacts lens 3, then part *a* was inserted. The housing was then rotated 180° about a horizontal axis. Parts *l* and *m* were inserted. Lens 4 was inserted. Part *o* was screwed in using a spanner wrench until it contacted lens 4.

The zoom assembly was secured to an optical table and collimated laser light was shown through it. The plungers were carefully screwed in using the spanner wrench until the light emerged collimated from the zoom assembly. At this point both of the lenses were 50% compressed and the slider naturally came to rest at the equilibrium position between the lenses. The zoom assembly was then removed from the optical table.

Lens 2 was set in the first mount and the spacer was screwed in using a spanner wrench. Lens 1 was set on the spacer ledge and the retaining ring was screwed in with a spanner wrench to hold lens 1 in place. The mount was screwed into the assembly housing until it made contact with part *a*. Lens #5 was dropped into its mount and the retaining ring was screwed down to hold it in place using a spanner wrench. The second mount was screwed into the assembly housing using a spanner wrench until it made contact with part *o*.

The two servo brackets were slipped over the outside of the assembly housing and the servo was secured to them using screws through the post slots. The servo position was adjusted until it lined up with the rack, and then it was lowered until the pinion and rack meshed. The bracket set screws were tightened, and then the bracket post screws were tightened. Finally, the camera adapter (with the camera already screwed on) was slipped over the assembly housing. The camera adapter position was adjusted until the image was in focus, and then the three camera adapter set screws were tightened.

The entire assembly was set inside the UAV nose (figure 15) with the two housing brackets flush with the inside of the nose on either side of the side camera port. Screws were threaded through the wall and through the bracket holes. Lock washers and nuts were then threaded onto the screws and tightened. A wedge shaped bracket was then inserted between the SWIR camera and the opposite wall and similarly attached.

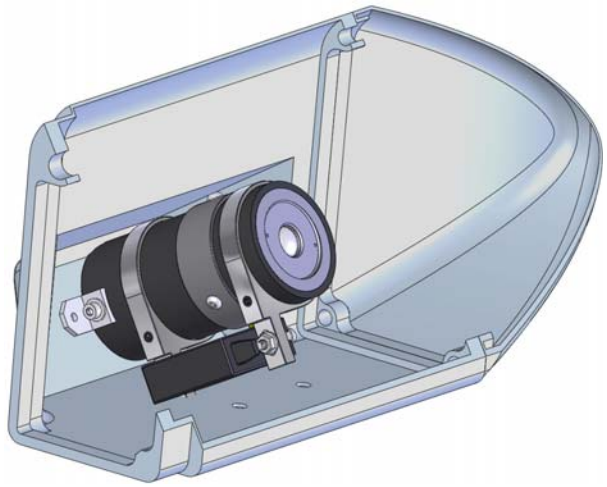


FIG 15 Cut away view of prototype 2.0 mounted in UAV nose using housing brackets.

Results

FIG 16 Assembled zoom system utilizing tunable GRIN lenses.

The completed prototype (figure 16) was tested in the laboratory, on rooftops at NRL and in a UAV test flight. The servo attachment to the housing worked well; the servo remained steady and it was easy to remove backlash from the pinion/rack interface during setup. All of the fixed focal length lens mounts worked as expected and were simple to assemble. The tunable lens assembly also worked as expected and did not bind. The servo had sufficient torque to compress the lenses the amount proscribed by the optical designers. The entire assembly fit in the UAV nose and was mounted to the nose as designed.

The camera adapter was a clumsy and awkward way to adjust the BFL that was difficult to adjust precisely. The three set screws tended to force the camera out of focus when tightened by bearing unevenly on the housing and changing the BFL. A better design would have been a fine-pitch threaded adapter. This would have given the user more accurate BFL control and maintained better camera-lens alignment.

The machinist pointed out that it would be much simpler to fabricate the housing if the nose attachment brackets were an integral part of it, rather than screwed on. This part of the design was changed. The anodized parts still reflected significant light due to the smooth finish; they should have been glass beaded before anodization, which would have yielded a flat black finish.

Some components (such as the housing, brackets and fixed focal length lens mounts) were much stronger than necessary and could have been made smaller/thinner to reduce the assembly mass.

Mechanical Zoom GRIN System (Prototype 3.4) – Approach #3

FIG 17 SolidWorks rendering of prototype 3.4 with SWIR camera.

The completed prototype is illustrated in figure 17. The optical design consists of six elements (see figure 18 and Table V). Elements 1, 2, 3 and 4 translate along the optical axis as the system zooms, while elements 5 and 6 are fixed. Element 1 moves independently, whereas elements 2, 3 and 4 are grouped and moved together. The motions of element 1 and the group are non-linear, with respect to the fixed components and to each other. This non-linearity and the proscribed change in aperture diameter made a simple coupling difficult to design or fabricate. A cam based design was chosen because it allowed a single component to drive all of the lens translations and aperture diameter change. The lens positions and aperture diameter could be encoded in the geometry of three slots, so that the angular displacement of the cam would specify the system zoom state. The cam rotation could then be driven by any one of several actuation technologies or by hand.

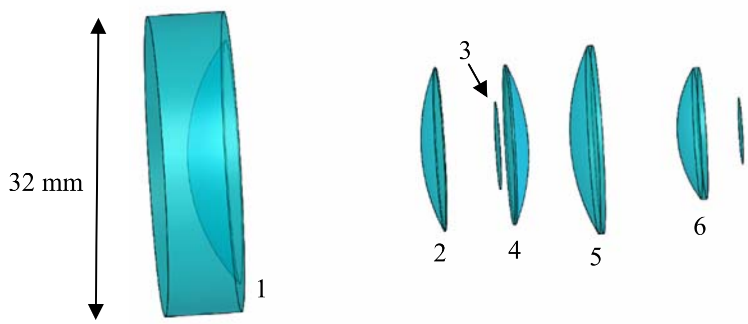


FIG 18 The six element optical design for prototype 3.4.

TABLE V. Optical elements in prototype 2.0

Element	Geometry	Type	Purpose	Translation/Mount
1	Plano-concave	Isotropic polycarbonate	Wide field of view	Yes/1
2	Plano-convex	Polymer GRIN	Change image magnification	Yes/2
3	Aperture	Variable diameter	Hold F/# constant	Yes/2
4	Plano-convex	Polymer GRIN	Change image magnification	Yes/2
5	Convex-concave	Isotropic polycarbonate	Capture light from lenses 2 & 4	No/3
6	Convex-concave	Isotropic polycarbonate	Focus image onto focal plane	No/3

The polycarbonate lenses were designed by NRL Optical Sciences and fabricated via diamond turning in a traditional optics shop. The polymer GRIN lenses were also designed by NRL Optical Sciences, but then fabricated at CWRU using the CWRU/NRL process. The variable aperture (Edmunds Optics P/N NT57-577) is a 30mm diameter black anodized aluminum disk with 12 anti-reflection coated leaves that open to a maximum aperture of 20mm. Aperture diameter is driven by a pin which sweeps through an angular displacement of 93° for complete transition from closed to full open.

Mechanical Design Requirements

This was the last prototype built by the BOSS program at NRL, and as such it incorporated many of the lessons learned from earlier prototypes. The mechanical design requirements provide evidence of this by the greater specificity and tighter tolerances (see table VI).

TABLE VI. Prototype 3.4 mechanical design requirements

Characteristic	Value
Maximum mass (including actuation)	150 g
Maximum length (including camera)	10 cm
Fixed lens position accuracy	±0.200mm
Fixed lens angular (tilt) accuracy	±3°
Lens concentricity	±0.150mm
Temperature range	10-45°C
Minimum BFL adjustment	±1.5 mm from design focus

Prototype 3.4 was not designed for integration in a UAV nose. Test flights with prototype 2.0 showed that these GRIN lens based zoom systems could be flown on a small UAV and return real-time variable magnification video to the ground station. Prototypes following 2.0 were not designed to be test flown because there was little to be gained by subsequent flights. This way greater resources could be dedicated to prototype development and improving the optics.

Component Design

Lens Fixturing, Guides and Housing
Mounts to hold each lens in place were designed in accordance with the tolerances specified by Optical Sciences. Lens 1 had its own mount; lenses 2 & 4 and the aperture were fitted in a second mount and lenses 5 & 6 were placed in a third mount. See figures 21-26 for rendered, cross section and exploded views of the mounts.

Mount 1 (see figures 21 and 22) consists of a cylindrical shell, open at both ends, with an internal ledge for lens 1 to rest on. The right[3] lens surface has a chamfer; the ledge fillet was sized so that they would not interfere. The mount has internal threads at the left end for a retaining ring that screws in against the flat lens surface to hold it in place. The retaining ring has two 1mm diameter holes on opposite sides of the left surface for a spanner wrench. The inside surface of the mount in contact with the lens is a smooth bore and is the primary means of maintaining centricity. Both the ledge and retaining ring determine the tilt angle of the lens with respect to the optical axis. This simple mount was possible because of the cylindrical cross section of the lens, which does not require any chamfered or curved surfaces to maintain the correct lens position. (8)

The second mount (see figures 23 and 24) consists of parts A and B. Part A is a cylinder with a center bore, a ledge for lens 4 and a recess for the aperture. The ledge is followed to the right by a chamfer to avoid vignetting and ease insertion of the lens. The left side of part A has internal threads to accommodate part B, which is a disk with external threads and a ledge for lens 2. Part B screws into part A from the left until it makes contact with a ledge, establishing the correct distance between lenses 2 & 4. Before part B is screwed in to part A a thin rubber annulus is laid on top of the aperture. Part B would retains the aperture in position by compressing the rubber between them, but the distance between lenses 2 & 4 is dictated by the ledge in part A, not the less precise aperture dimensions. There are two 1mm diameter holes on opposite sides of the left surface of part B for a spanner wrench. Neither lens 2 nor lens 4 has a retaining

[3] A note on conventions used in this paper: In diagrams, light always flows from left to right. Surfaces perpendicular to the optical axis are therefore either facing left or facing right.

ring; instead they are fixed to the mount using three small drops of Devcon 5-minute epoxy. A more compliant method of retention would have been preferable, but the required lens motions did not allow enough space. (8) The inside walls of the ledges provide centering for both lenses. Tilt angle is determined by the flat surface of the ledge, assuming the lens rests in contact with it over the whole circumference when epoxy is applied. The aperture pin is a cylinder with external threads at one end and a screw driver slot at the other. It emerges through a slot in part A and protrudes slightly beyond it.

The third mount (see figures 25 and 26) accommodates lenses 5 & 6, which are in fixed positions relative to the FPA and housing. It has two ledges to accommodate the lenses, one at the left end and one at the right end. Lens 5 is retained by a rubber O-ring (McMaster part number 9559K19) which was fixed to the mount by three drops of Devcon 5-minute epoxy. This retention method was chosen because it provides greater compliance than adhering the lens directly to the mount and there is insufficient radial space for a threaded retaining ring. Lens 6 is held in place by a retaining ring but there is insufficient radial space for threads between the lens and camera case C-mount, so it is press fit into the mount. The Delrin retaining ring has a shelf to accommodate the right side of the lens and provide some concentricity control, but the main driver of concentricity is the chamfer on the mount ledge. At the point of contact with the lens surface, the difference in tangential angle between the back and front surface of lens 6 must be greater than 17° to provide sufficient axial pre-load to center the lens. (9) The point of contact for the back surface is the flat retaining ring, so $\varphi_2 = 0$ and $y_{c2} = ½ D_{g2}$. The contact point and angle of the front of the lens were determined using equations 4 and 5, with the lens geometry parameters illustrated in figure 19. In this case $\varphi_1 = 20.8°$, so the chamfer in the mount ledge provides sufficient axial pre-load to center the lens. The values of parameters in figure 19 are listed in table VII.

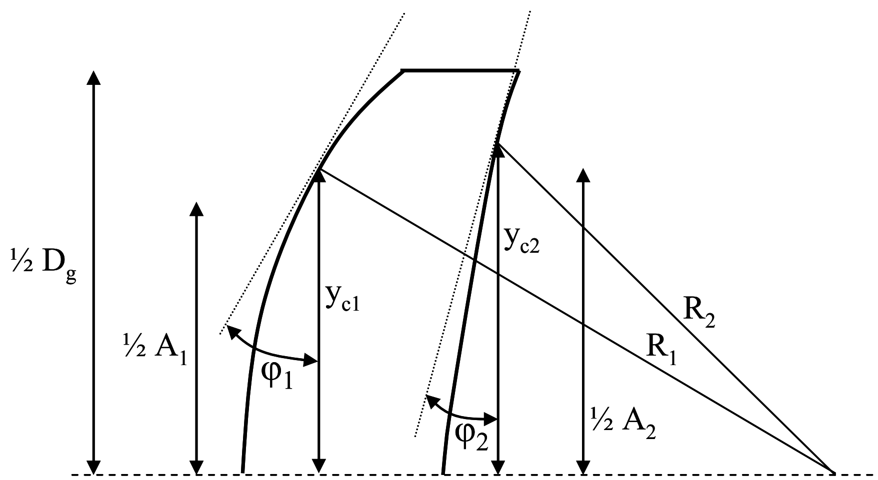


FIG 19 Parameters for calculation of lens surface angles at contact points, to ensure sufficient axial preload for centering of lens. D_g is lens diameter, A is open aperture diameter, y_c is distance between contact point and optical axis, R is the lens surface radius of curvature and φ is the contact angle.

TABLE VII. Dimensions of lens 6 SolidWorks model in prototype 3.4

Dimension	Value
D_g	14.000 mm
R_1	12.628 mm
R_2	54.12 mm
A_1	12.68 mm
A_2	12.68 mm
φ_1	20.8°
φ_2	0°

The radial distances from the optical axis to the lens-fixture contact points are given by equation 4, and the contact angles are given by equation 5. These parameters are dependent on the front and back open apertures (A_1 and A_2) the diameter of the lens D_g and the radii of the front and back lens surfaces (R_1 and R_2). Equation 6 describes the difference in contact angles required in order to center the lens using the retention forces from the mount.

$$y_{c1} = \frac{A_1 + D_g}{4} \qquad y_{c2} = \frac{A_2 + D_g}{4} \tag{4}$$

$$\varphi_1 = \tan^{-1}\left(\frac{y_{c1}}{R_1}\right) \qquad \varphi_2 = \tan^{-1}\left(\frac{y_{c2}}{R_2}\right) \tag{5}$$

$$\left|\varphi_1 - \varphi_2\right| \geq 17^\circ \tag{6}$$

Lens 6 makes contact with the chamfered ledge at a point offset from the start of the ledge. The magnitude of this offset is dictated by y_c and the lens curvature (figure 20). To ensure the lens is positioned correctly along the optical axis, this offset was computed and added to the ledge height. This computation was made simpler by assuming the lens makes contact at the chamfer mid point, which is the most stable condition anyway. Figure 19 illustrates the geometry of equations 7 and 8. The chamfer width was chosen arbitrarily based on ease of fabrication; however it had to maintain $2r_c \geq A_1$ to avoid vignetting.

$$d = \frac{1}{2} w_c \sin\varphi \tag{7}$$

$$r_c = y_c - \frac{1}{2} w_c \cos\varphi \tag{8}$$

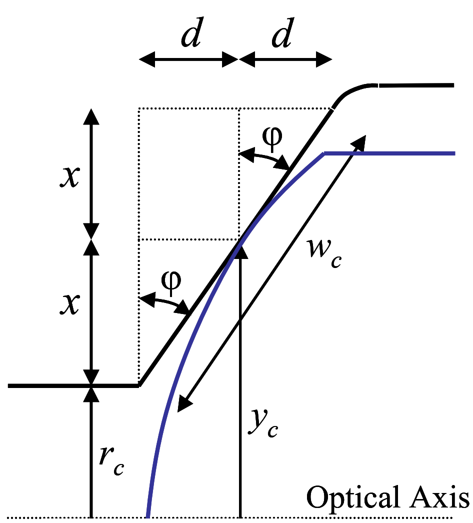


FIG 20 Parameters for calculation of the offset from the point of contact between lens and chamfered ledge. y_c is distance between contact point and optical axis, φ is the contact angle and chamfer angle, w_c is chamfer breadth, x is ½ chamfer height, d is ½ chamfer width and r_c is radius of inside surface of chamfer.

Mount 3 has two sets of external threads; on the left side are threads that screw into the housing and on the right side are threads that screw into the camera. A flange on mount 3 stops it when screwed into the back of the housing. Mount 3 threads into the camera housing until the flange contacts the camera housing or thin steel shims placed between the mount and camera housing stop its travel. The shims are used to adjust the BFL and bring the image into focus. When no shims are used, the flange width allows the mount to nearly touch the glass FPA cover, but not make contact. Allowing adjustment of the BFL is advisable in the design of most optical systems, but in this case was critical. Sensors Unlimited was unable to provide accurate effective path length data for light passing through the glass FPA cover, air gap and InGaAs “flip-chip” because their design assumed that all optics used with the camera would have built in BFL adjustment. Additionally, the short BFL in this optical design made the system particularly sensitive to small errors in BFL, and the only practical means of accommodating this is to build in adjustment. There are two 1mm diameter spanner wrench holes in the left face of the mount 180° apart.

FIG 21 Isometric rendering and cross section of prototype 3.4 mount for lens 1.

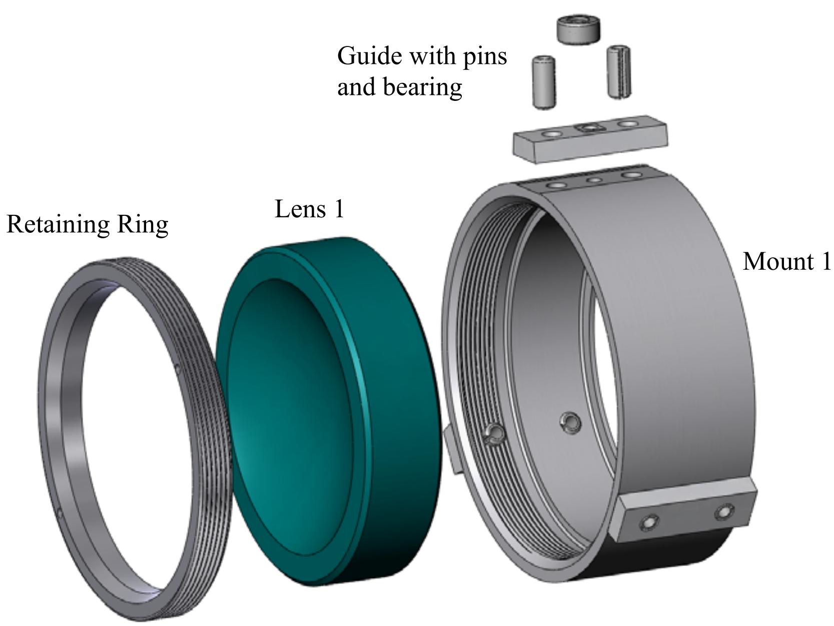


FIG 22 Exploded view of prototype 3.4 mount one for lens 1.

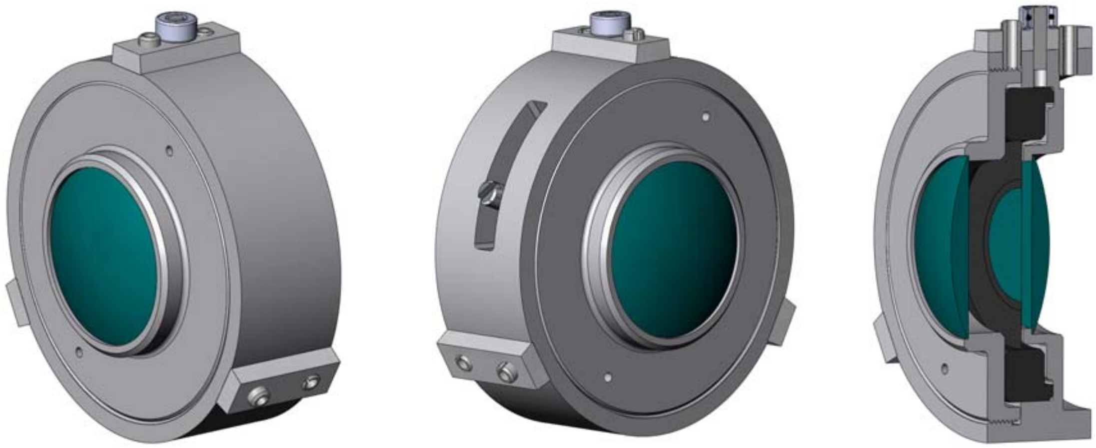


FIG 23 Isometric renderings and cross section of prototype 3.4 mount for lenses 2&4 and the aperture.

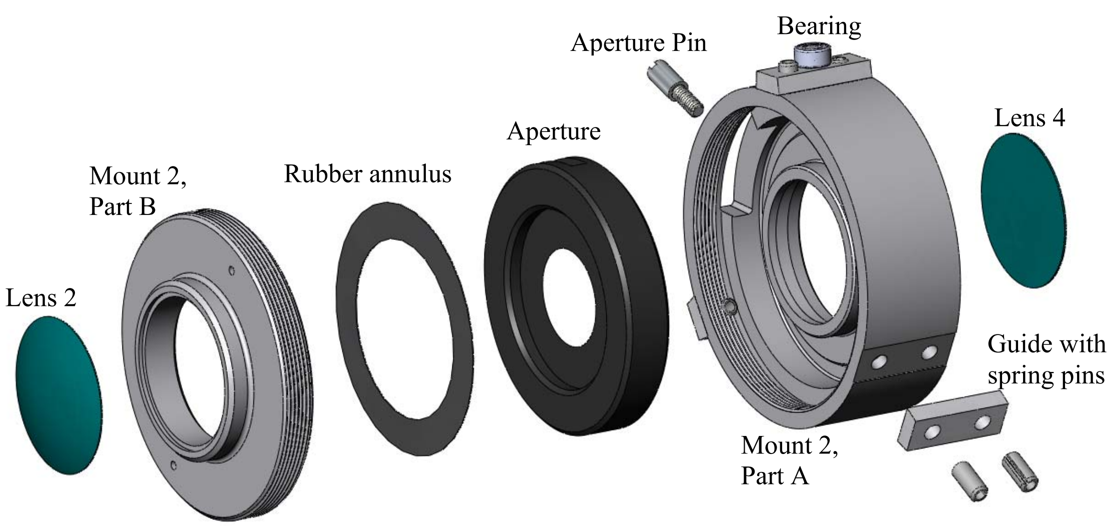


FIG 24 Exploded view of prototype 3.4 mount two for lenses 2&4 and the aperture. Part B is the smaller component screwed into part A.

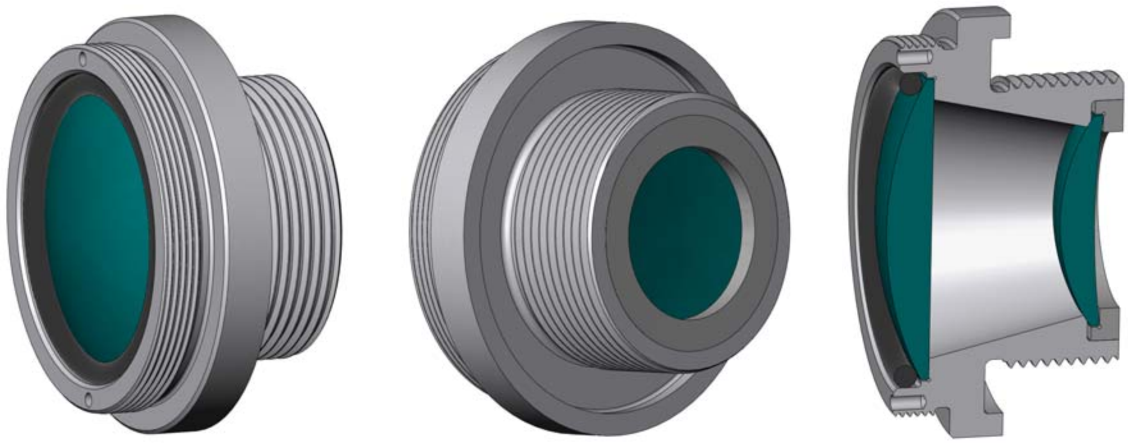


FIG 25 Isometric renderings and cross section of prototype 3.4 mount for lenses 5&6.

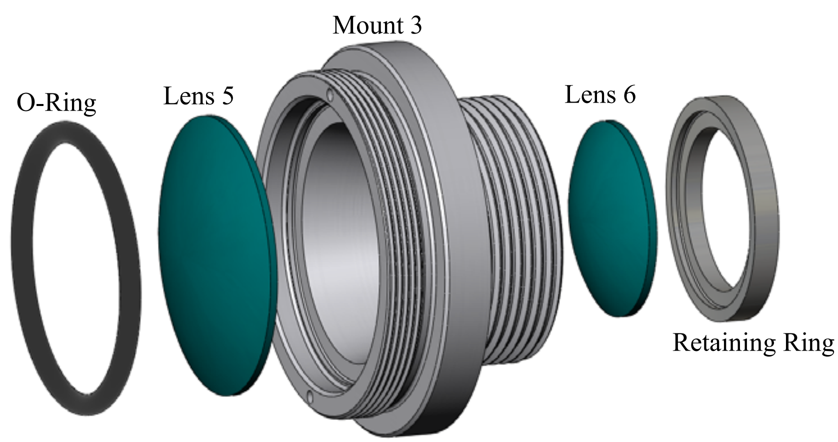


FIG 26 Exploded view of prototype 3.4 mount for lenses 5&6.

The housing forms the backbone of the system with all other components attached to it in some way. It is a cylinder with three slots at 120° intervals about the optical axis. Mounts 1 and 2 are housed in the left side and mount 3 is screwed into the right side. A flange extends from the right side into the cylinder to provide sufficient thread engagement for the third mount. A flange at the right end of the housing acts as a thrust bearing to constrain the cam. Two broad grooves in the outside of the housing reduce the likelihood of dirt or dust being trapped between the housing and cam, which could cause them to bind. In order to bolt on a bracket for the actuation system, threaded holes are provided around the perimeter of the right face of the housing.

Three threaded holes at the left end of the housing accommodate screws to retain the other cam thrust bearing, which is a narrow ring (figure 27). The screws pass through slots in the ring rather than holes, so that the force constraining the cam position along the optical axis can be adjusted. This way the friction between the cam and ring at one end, and between the cam and bearing flange at the other end can be kept to a minimum. Secondary functions of this ring include:

- Providing the housing with rigidity and maintaining slot width when the guides push on it. If not for this ring, the three "fingers" of the housing would be pushed outward by the tapered guides when the cam drives the lens mounts.
- Adjusting the normal force between the cam and housing. Adjusting the torque on the three screws forces the three "fingers" of the housing to expand or contract radially. This changes the friction force resisting cam rotation and the accuracy of cam centering on the optical axis. In this

case friction and centering are inversely proportional. This adjustment has a similar effect on the friction resisting movement of the lens mounts.

The three screws make contact with the ring on flat sections of the ring outside diameter. These sections were flattened to provide sufficient contact area between the screw heads and ring to prevent the ring from "walking" out of position. Lock washers inserted between the screw heads and ring against at the flat sections also help to prevent loosening of the ring.

The system zooms when the first two mounts translate along the optical axis. So they translate smoothly, each mount rests on three Delrin guides at 120° intervals about the optical axis, which are captured by the slots in the housing. The guides rest against flat sections on the outside surface of the mounts and are held to the mounts by steel spring pins. The 7° taper on both the guides and guide slots ensure positive capture of the mounts and force the mounts to concentric positions in the housing. The mounts can easily slide along the optical axis on the guides without binding. The guide width and length were determined using the rule of thumb that sliding components three times longer than they are wide will not bind. Three guides were used for each mount because two guides would not constrain pitch and yaw tilt errors as effectively. Each mount also has a 4mm outside diameter bearing (Dynaroll shielded bearing P/N 681XhZZ) press-fit to a steel dowel pin (McMaster P/N 91585A007) in one guide. The cam acts on these bearings to drive the mount translation in the housing. The inner bearing race rests on a square 0.13 mm high platform on the bearing guide to prevent contact between the outer bearing race and the guide. Renderings in figures 28 and 29 show the mount/housing assembly. Figures 30 and 31 show the housing assembled with lens mounts.

FIG 27 Cam thrust bearing ring.

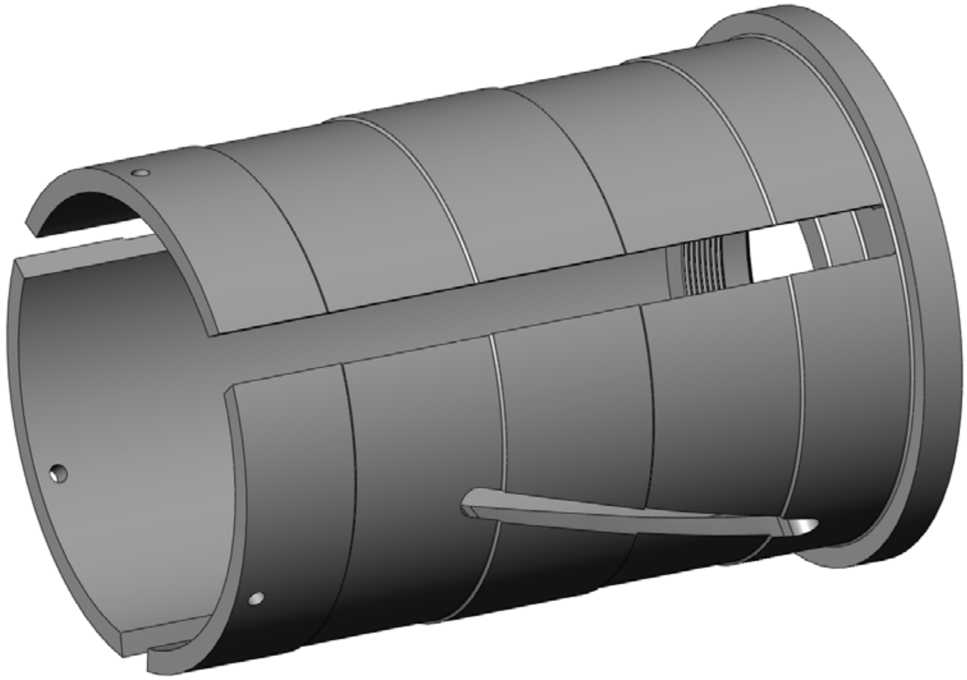


FIG 28 Rendering of housing for prototype 3.4.

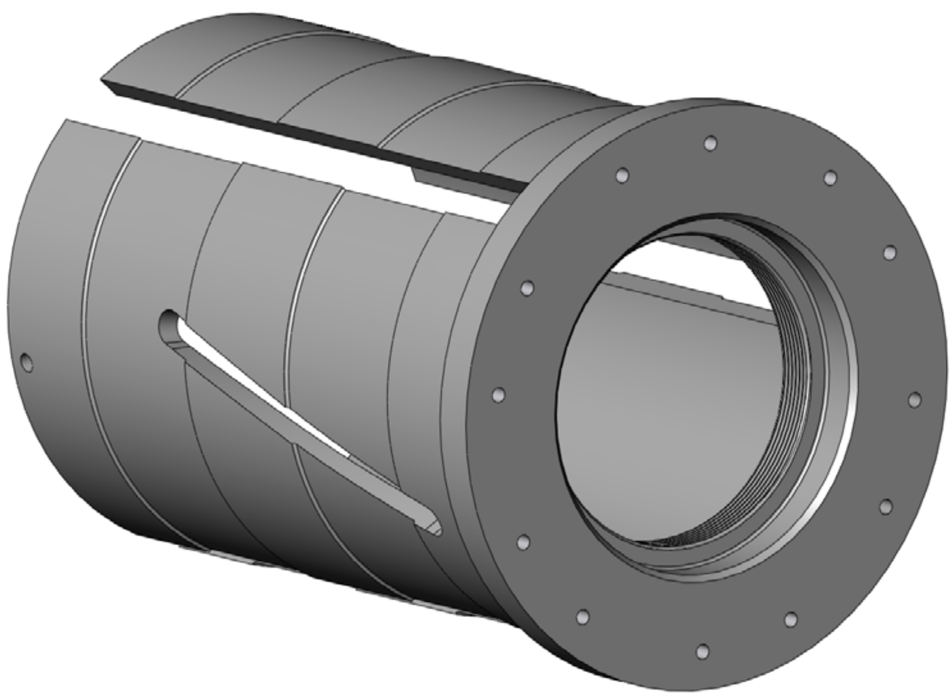


FIG 29 Rendering of housing for prototype 3.4.

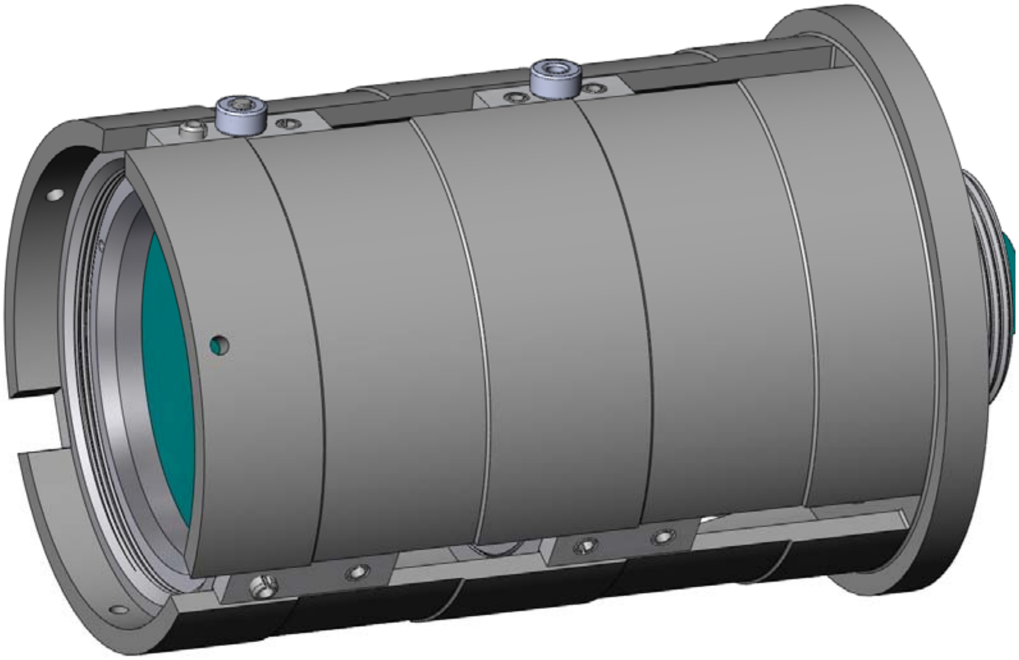


FIG 30 Rendering of mount/housing assembly in prototype 3.4.

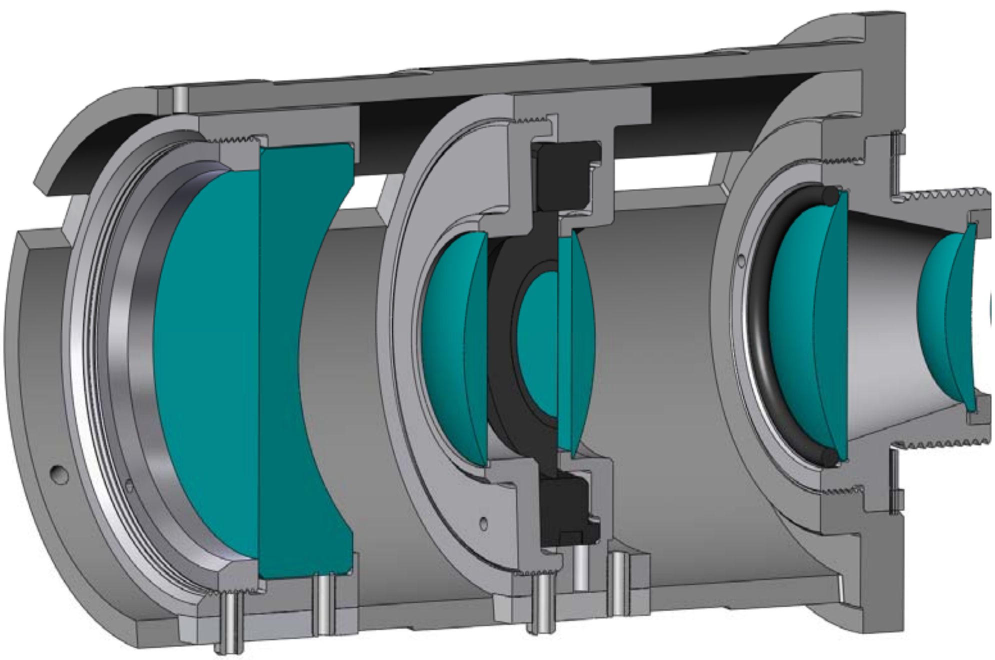


FIG 31 Cross section view of mount/housing assembly in prototype 3.4.

All mount components are 6061-T6 aluminum, glass beaded and then hard coat anodized black. The glass beading step adds minor surface roughness that significantly reduces reflectivity when anodized black. Low reflectivity mount components are desired to avoid reflecting stray light back into the optical path, which can lead to poor image quality. The guides are made of Delrin because of its natural lubricity, machinability and strength. The housing is also made of 6061-T6 aluminum, glass beaded and then hard coat anodized black; but a third finishing step was added. The anodized finish is impregnated with Teflon (driven into the porous Al_2O_3 surface coating) to increase the lubricity of the surface. The cam thrust bearing (ring) received the same treatment. Teflon impregnation reduces the force required to drive the guides over the guide rails and drive the cam rotation.

Tolerancing and Thermal Calculations
Differing coefficients of thermal expansion between the lenses and mounts were accounted for to avoid two problems. First, thermal stresses can induce birefringence in lenses by creating directionally dependant indices of refraction related to the stress vector in the material. Second, thermal expansion or contraction constrained by the mount can cause deviation from the desired lens surface geometry.

The coefficients of thermal expansion for polycarbonate and 6061-T6 aluminum are $\alpha_{PC} = 6.90\text{x}10^{-5}$ mm/mm·K and $\alpha_{6061T6} = 2.36\text{x}10^{-5}$ mm/mm·K. The coefficient of thermal expansion for the GRIN lens material is unknown, but because polycarbonate is a major component, α_{PC} was expected to be a reasonable approximation. The lenses contract more quickly than the fixture when the temperature falls ($\alpha_{PC} > \alpha_{6061T6}$), so temperature reductions are not a major concern. In the worst case scenario, when the temperature falls the lenses will decenter as the clamping force from the retaining ring is reduced. Because the retaining rings and lenses meet at nearly the narrowest lens dimension however, the percentage change in clamping force is expected to be small and inconsequential. For this reason, temperature based adjustments to fixture inner diameter assume a scenario in which the assembly is warmed from T_{min} to T_{max} with the lenses starting at their nominal diameters. In this case, ΔT=50K. For each fixture, the bottom of the inner diameter tolerance band is given by equation 9 in terms of the lens nominal radius and upper radial tolerance.

$$R_{fixture\_ID\_lower} = \frac{1 + \Delta T \alpha_{PC}}{1 + \Delta T \alpha_{6061T6}} \left(R_{lens\_nominal} + \varepsilon_{lens\_upper} \right) \quad [9]$$

Another consideration is the accuracy with which the parts are to be fabricated. Equation 9 provides the temperature adjusted bottom of the fixture inner diameter tolerance band. To obtain the nominal and upper fixture inner diameters, the tolerances must included.

$$R_{fixture\_ID\_nominal} = R_{fixture\_ID\_lower} + \varepsilon_{fixture\_ID\_lower} \quad [10]$$

$$R_{fixture\_ID\_upper} = R_{fixture\_ID\_nominal} + \varepsilon_{fixture\_ID\_upper} \quad [11]$$

The requirements for this design specify that $\varepsilon_{\text{fixture_ID_lower}} = \varepsilon_{\text{fixture_ID_upper}} = 0.150$mm. This process was used to determine the nominal inner diameter of each fixture. Most other components in prototype 3.4 and the camera are 6061-T6 aluminum; hence the interfaces among them will not be affected by temperature changes. Some steel fasteners were used, but the minor thermal stresses at those junctions should have little effect on performance. All of the lenses were constrained radially by aluminum mounts except for lens 6, which had a Delrin mount. The same fractional change in diameter used for the other lenses was applied to lens 6 because the coefficient of thermal expansion of Delrin $\alpha_{Delrin} = 6.80\text{x}10^{-5}$ mm/mm·K is close to that of aluminum.

Cam, Cam Bearings and Aperture Pin Slot
This design utilizes a closed-track cylinder cam with roller followers in which the cam rotates and the followers translate (figure 32). The cam is embodied as a sleeve with slots cut in it, which is wrapped around the housing. The cam rests directly on the housing and can rotate about the optical axis but is prevented by thrust bearings from translating along the optical axis. When the cam rotates, bearings captured in its slots are forced to translate along the optical axis. The lens mounts are pinned to and follow the bearings, so that the lens positions are directly related to the angular position of the cam.

The aperture diameter is controlled by a secondary closed-track cylinder cam with a cylindrical follower. In this case the cam (the housing) is stationary and the follower both translates and rotates. The aperture pin protrudes from mount 3 and is captured in a curved slot in the housing. When the aperture translates along the optical axis with mount 3, the slot geometry drives the aperture pin through a swept angle perpendicular to the optical axis. As the pin angle changes, the aperture opens or closes.

The design provided by Optical Sciences included the distance between each pair of lenses in the optical train at several points in the zoom process. Effective focal length (EFL) was used as the independent variable because it is tied directly to the image magnification (zoom), and can be thought of as a "state variable" for the system. The front surface of lens 5 was initially chosen to be the static frame of reference for the mechanical design, and a coordinate transform was applied to the lens separation data to yield distances from lens 5. These data were then plotted as a function of EFL to produce two curves describing lens motion (figure 33). A third curve was added to describe aperture diameter as a function of EFL.

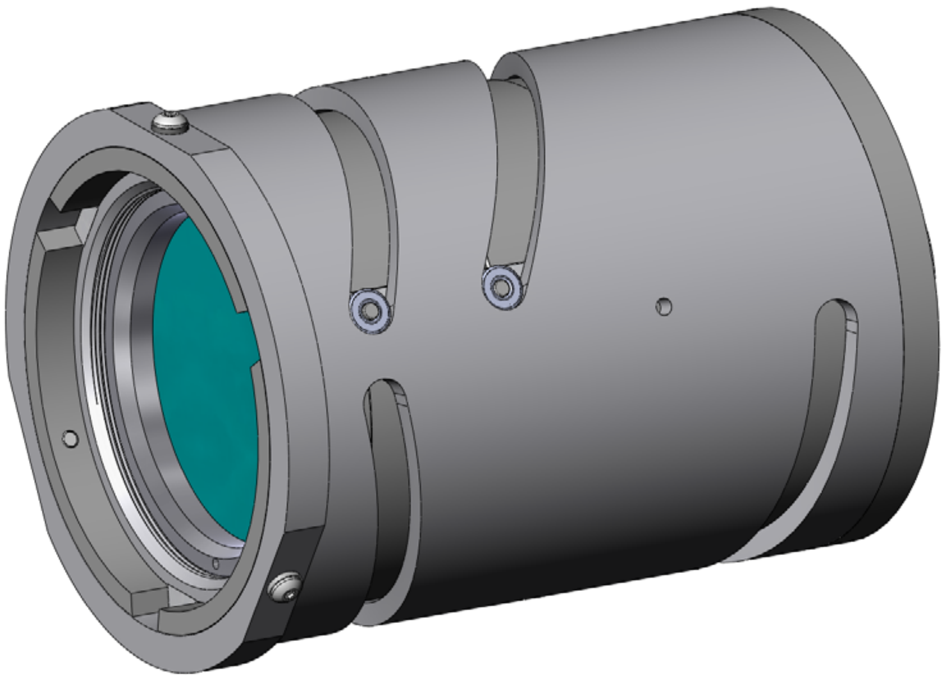


FIG 32 Cam installed on housing with lens mount bearings captured in slots and left side thrust bearing.

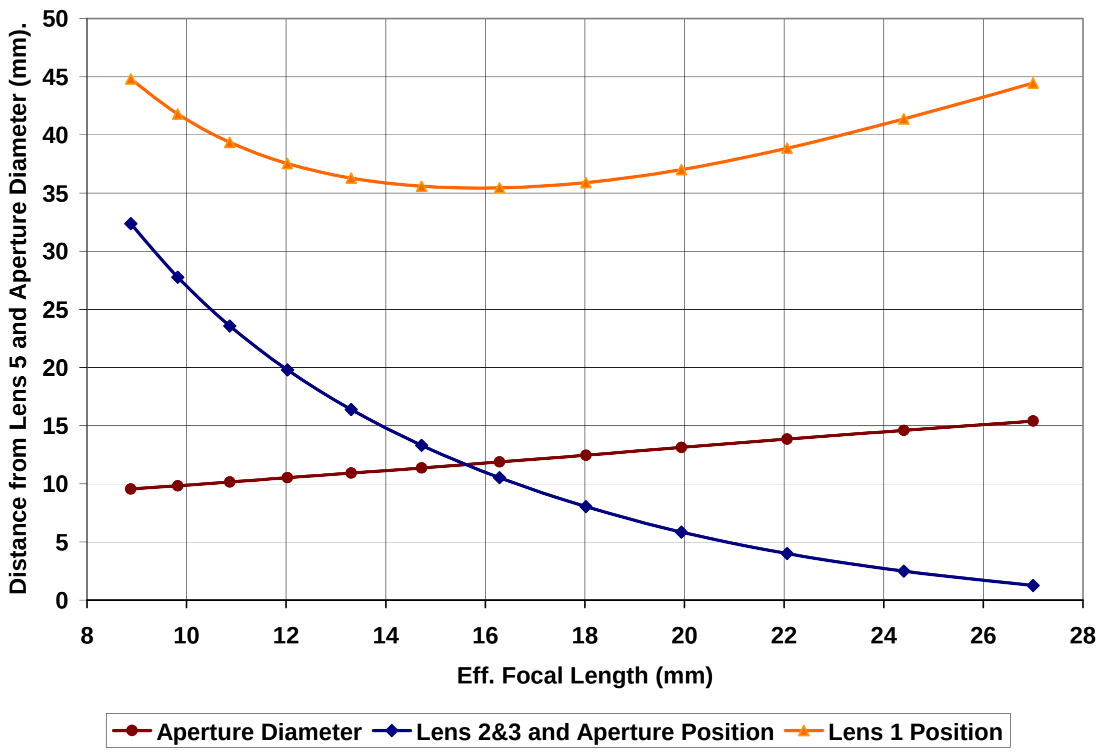


FIG 33 Lens and aperture motions

The basic process used to design the cam consisted of wrapping these curves over the cam surface to describe the slot geometry. There were several complications added to the process:

- These slots cannot occupy the entire 2π radians of the cam circumference or the slot for mount 1 will self-intersect and the cam will fall apart. Material must be left between the slot ends to leave the cam with some structural integrity.

- In cylinder cam systems, the pitch angle $\theta_{pressure}$ is the angle between the force vector on a cam follower and the direction of cam follower travel (see figure 34). The pitch angle is dictated by the slope of the cam surface. As a rule of thumb, the pitch angle of a cylinder cam should not exceed 30° or the cam follower will bind. (6) Given a particular slot geometry, the slot slope can be reduced by spreading the curve over a larger diameter cam or stretching it over a larger fraction of the cam circumference.

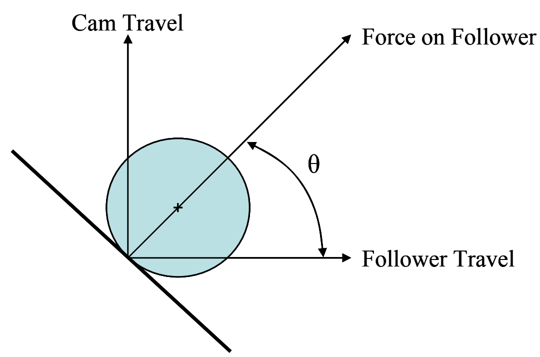


FIG 34 Pressure angle of cam follower (a bearing, in this case) and cam slot wall.

- The curves in figure 33 describe the location of a lens surface, but the bearing for that lens mount may be pinned to a point on the mount that is offset from the lens surface. When converting the curves into slot locations, the offset along the optical axis between the bearing/cam interface and the referenced lens surface must be accounted for.

- The thickness of the cam slot must be accounted for by shifting the curves by a distance equal to the follower radius, in both directions normal to the curve.

- When converting the curves into slot locations in a cam referenced coordinate system, the offset along the optical axis between lens 5 and the end of the cam must be accounted for. This will yield slot coordinates in a cylindrical coordinate system referenced to the cylinder, which can be used to cut the slots.

- The bearing must not be in contact with both sides of the cam slot simultaneously or it will bind. The cam slots must be slightly wider than the bearing outer diameter upper tolerance so that only one side of the bearing is in contact with the slot wall. This added width will be manifested as lens position error, however, so it must be kept as small as possible.

Finite element analysis (FEA) was used to optimize the gap between slot ends and identify the minimum width that will retain sufficient strength for operation and the fabrication process. FEA indicated that a gap of 3.5 mm was sufficient if the cam segments separated by slots maintain concentricity. The housing and cam sleeve maintain concentricity of the cam segments. A MathCAD worksheet was created to optimize for the smallest cam diameter within the 30° pressure angle limit and maximum angular spread dictated by the minimum gap between slot ends. Polynomial expressions 12 and 13 were fitted to the two curves describing lens 1 and 4 distance from lens 5 (figure 35). $h:\{0, h_{max}\}$ where h_{max} is the length of the cam and $|x|:\{0, \pi r\}$ where x is the position on the cam circumference and r is the cam outer radius as illustrated in figure 36; the units in both cases are mm. In MathCAD the derivative of each curve with respect to circumferential position on the cam was calculated. The pressure angle in degrees is then given by equations 14 and 15.

$$h_{mount1}(x) = 1.1520\times10^{-7}x^4 - 1.3440\times10^{-5}x^3 + 1.3942\times10^{-3}x^2 + 6.3807\times10^{-2} + 20.594 \quad [12]$$

$$h_{mount2}(x) = -1.2003\times10^{-5}x^3 + 1.5668\times10^{-3}x^2 - 0.1738x - 6.2659 \quad [13]$$

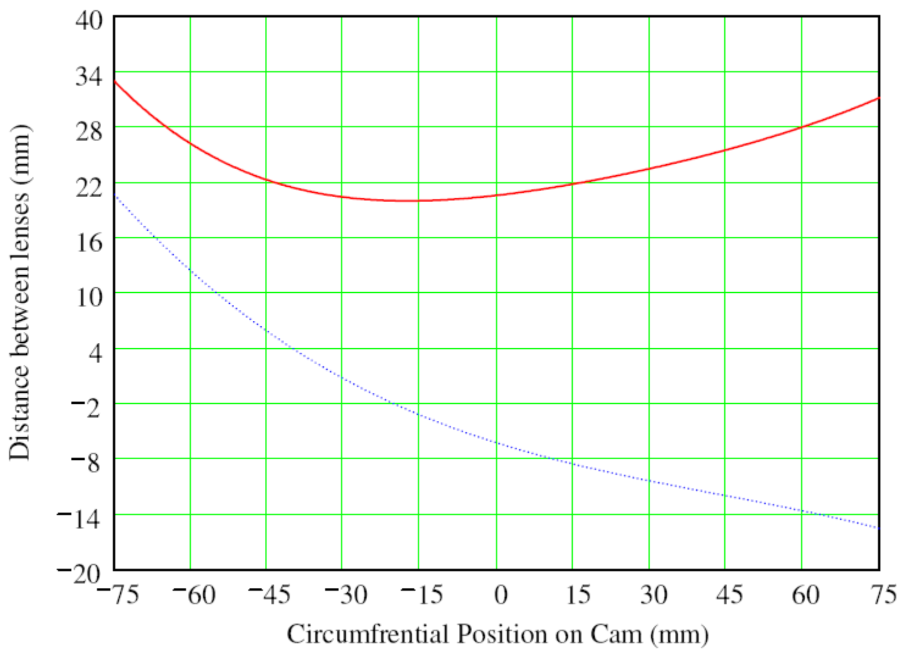


FIG 35 Distance from lens 5 to lens 1 (red) and to lens 4 (blue).

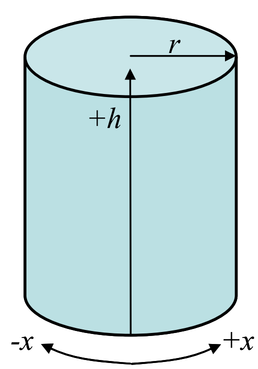


FIG 36 Cam oriented coordinate system used for slot specification.

$$h'_{mount1}(x) = \frac{d}{dx}h_{mount1(x)} \quad [14]$$

$$\theta_{pressure1} = \frac{180}{\pi}\tan^{-1}\left(h'_{mount1}(x)\right) \quad [15]$$

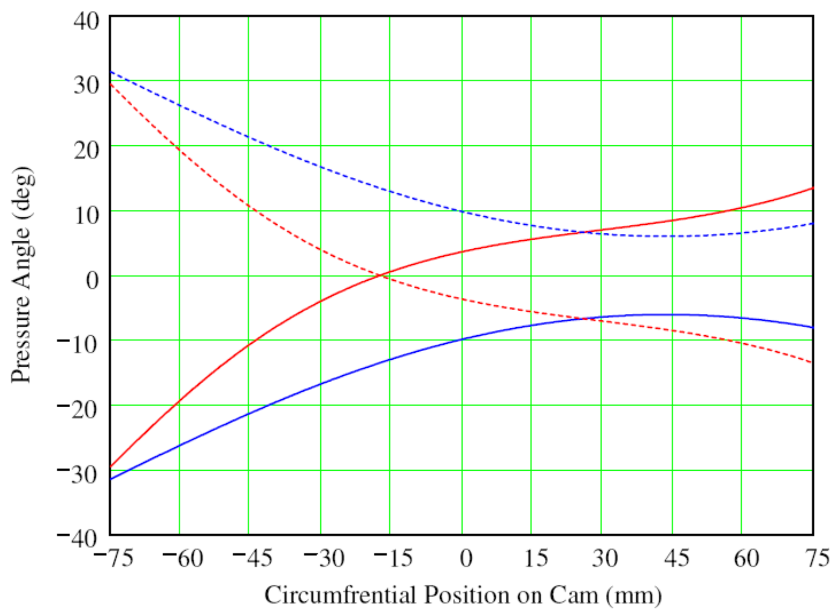


FIG 37 Pressure angle of both cam followers over the circumference of the cam. Lens 1 zoom in (red), lens 1 zoom out (dashed red), lenses 2&4 zoom in (blue), lenses 2&4 zoom out (dashed blue).

With the required gap between slot ends decided, the optimal cam diameters were found to be d_{cam_min}= 42 mm and d_{cam_max}= 46 mm. This inside diameter is the minimum required to keep the cam pressure angle absolute magnitude below 30° over the entire zoom range (see figure 37) for lens mount 2. The mount 1 slot slope is less aggressive and did not restrict the cam diameter. The lens position curves were scaled to take the cam diameter into account and replotted as distance from the left surface of lens 5 as a function of position on the cam circumference. The curves were then shifted to put them in a cylindrical coordinate system referenced to the right end of the cam.

A plane tangent to the cylinder surface was defined in SolidWorks and points extracted from the slot curves were plotted on it. Splines were fitted to the points and mirrored on both sides to yield slots profiles 0.2mm wider than the bearings. The slot ends were extended slightly beyond the optical specifications so that zooming through the full range would not produce a hard collision between the bearings and cam at each end. A soft limit could be programmed into the software controlling the actuation system to keep the lens motions inside proscribed limits. The plane was then wrapped onto the cylinder and the slot profiles were punched through to generate the cam part file (see figures 38 and 39).

The inside diameter edges of the cam are chamfered to ease insertion of the housing. There are five radial holes for dowel pins to secure a sleeve over the outside of the cam. The sleeve protects the lenses, bearings, etc. from dirt and blocks stray light that might otherwise enter the housing. It also provides the completed cam (figure 40) with additional structural rigidity so it does not act like a coil spring and deform when stressed.

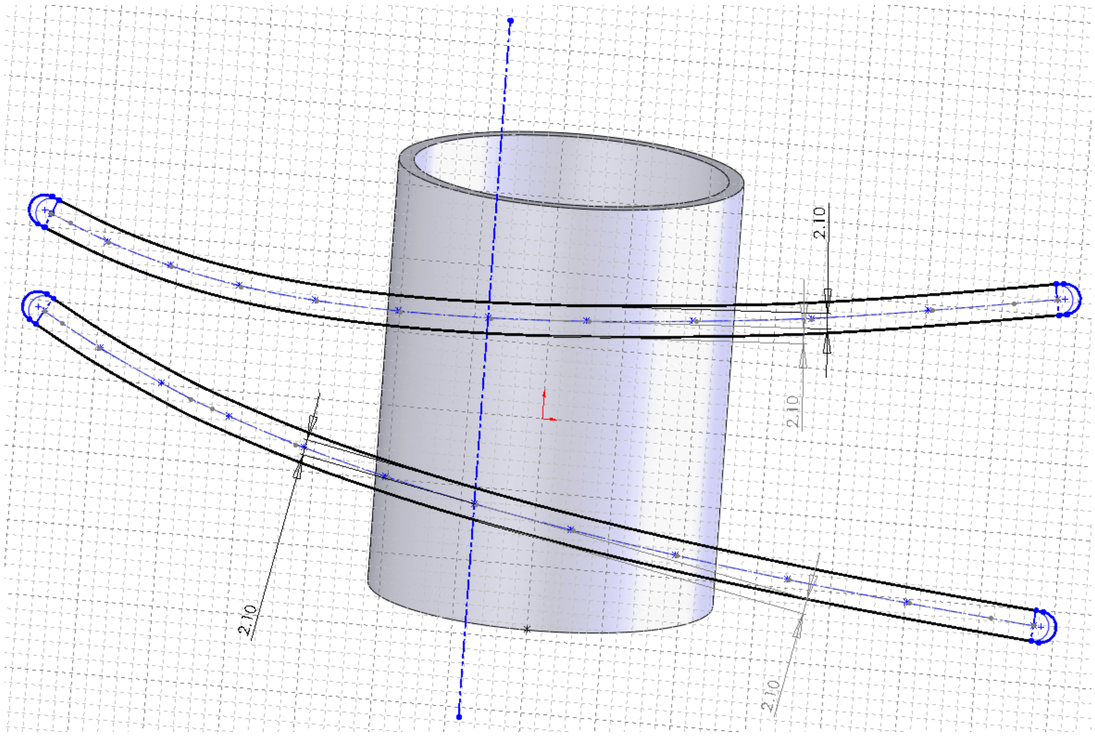


FIG 38 Cam slot profile generation in SolidWorks, based on lens position curves.

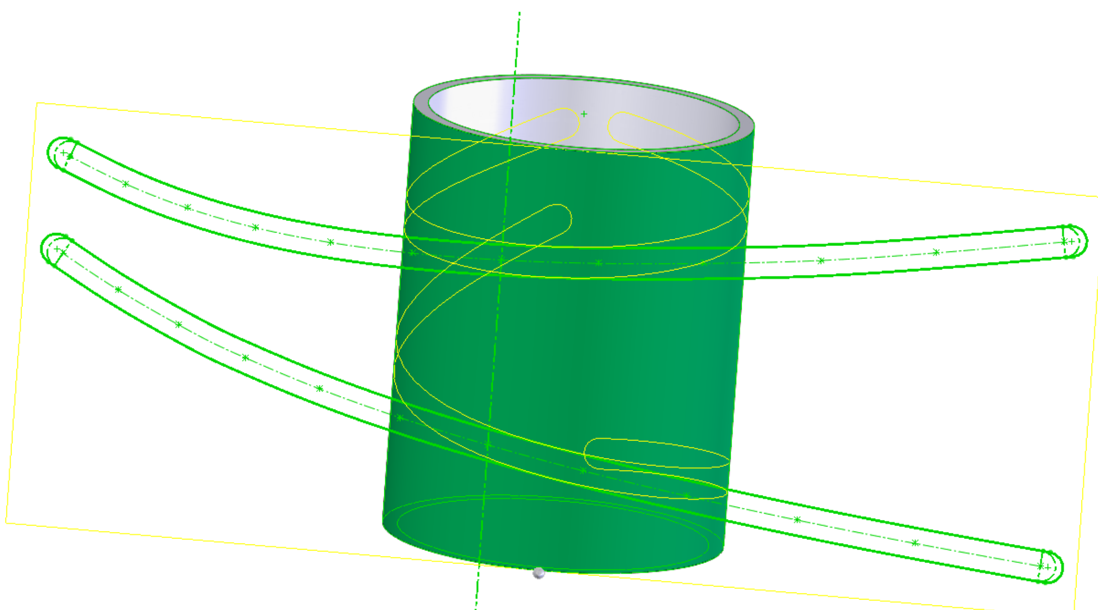


FIG 39 Coordinate transform and Boolean subtraction operations in SolidWorks to produce the cam slots.

FIG 40 Complete cam part model with slots, end chamfers and pins to secure sleeve.

The lens position error introduced by the 0.20mm added to the slot widths was calculated using equation 16. Because the maximum value of $\theta_{pressure}$ is approximately 30°, the error due to this dimension is not greater than $\varepsilon_{bearing\ slot} = \pm 0.09$ mm.

$$\varepsilon_{bearing\ slot} = 0.10\cos\theta_{pressure} \qquad [16]$$

The procedure for creating the aperture pin slot in the housing was largely the same as that used to create the cam, except for some additional steps to translate aperture diameter into linear pin position. The coordinate transform applied to the lens mount positions in figure 33 to yield distance from lens 5 was also applied to the curve describing aperture diameter. The goal was then to obtain a curve describing aperture pin position on the circumference of the housing which could be used to generate the slot in SolidWorks.

The diameter of the aperture as a function of pin angular position was measured at several points and plotted; then a curve was fitted to the data (see figure 41). The aperture diameter was found to vary linearly with aperture pin angular position. The curve fit expression was used to transform the aperture diameter curve from Optical Sciences into an aperture pin angular position curve. The minimum and maximum aperture diameters in the design bound this curve. The housing outside radius was then used to convert the angular position coordinates into linear position coordinates on the surface of the housing. A coordinate transform was applied to the aperture slot curve to index it to the right hand end of the housing. A plane was created in SolidWorks tangent to the center of one finger on the housing. Points from the aperture slot curve were plotted on the plane and a spline was fitted to the points. The spline was mirrored on both sides to yield a slot profile 0.3 mm wider than the aperture pin. The ends of the slot profile were closed and an additional 0.3 mm was provided at each end to prevent a hard collision when the aperture opens or closes to its full design extent. The plane was then wrapped around the housing and the slot profile was punched through to yield the housing aperture pin slot. The angular extents of the slot on the housing are small, so the gap and diameter optimization required for the cam were unnecessary here. The same cam-follower pressure angle calculations were carried out in MathCAD and $\theta_{pressure}$ was found to be much smaller than 30° (see figure 42).

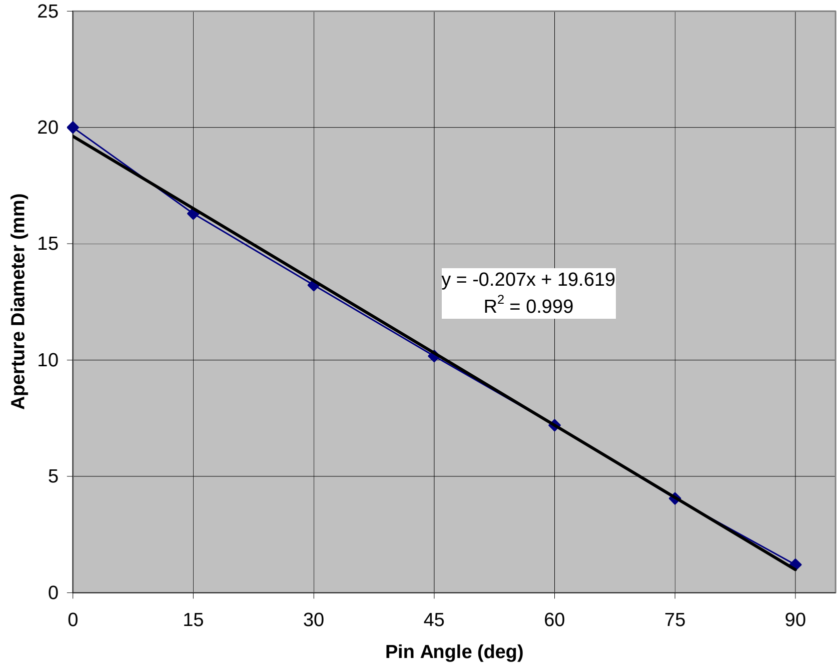


FIG 41 Measured aperture diameter as a function of aperture pin angle.

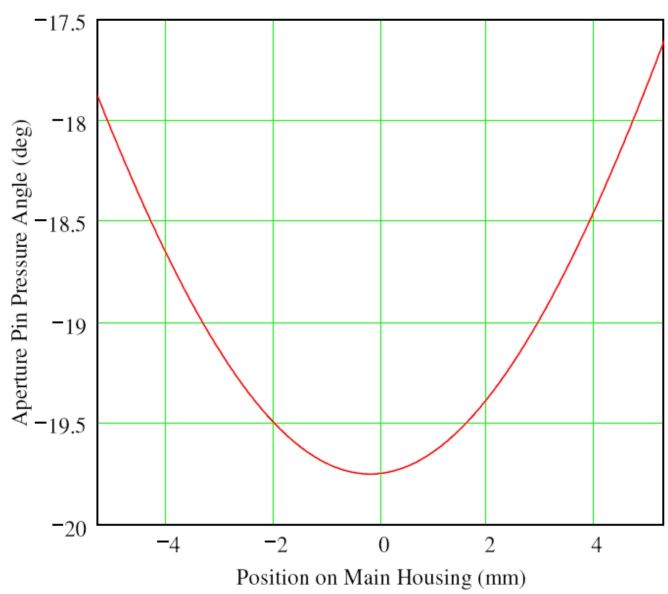


FIG 42 Aperture pin pressure angle over the circumference of the housing.

The error in aperture diameter due to the additional slot width was calculated using equation 17. This equation computes the linear error in pin location due to the additional slot width, then computes the angular error in radians, then converts radians to degrees and multiplies by the slope in figure 41 to obtain the diameter error.

$$\varepsilon_{aperture\ diameter} = 0.207\left(\frac{R_{main\ housing}}{0.15\cos\theta_{pressure\ aperture\ pin}}\right)\left(\frac{180}{\pi}\right) \qquad [17]$$

The cam and cam sleeve are made of 6061-T6 aluminum, glass beaded and hard coat anodized black. The cam is Teflon impregnated to reduce friction with the housing and thrust bearings. The aperture pin is steel.

Actuator Selection

The cam arrangement chosen to drive the zoom assembly in prototype 3.4 dictated the use of an actuator supplying torque (angular displacement). This precluded the use of several actuators in the study that produce linear displacements, such as piezoelectric stacks. The remaining actuation technologies appropriate for this application were servo motors and stepper motors. The study suggested that no servos small enough and light enough for this application are available outside of the hobby aircraft market. Unfortunately, experience with prototype 2.0 indicated that these devices did not have sufficient positional accuracy and were not documented well. The hobby servos were observed to frequently "hunt" for the commanded position and bog down. A lack of detailed performance information from the manufacturers limited our ability to model and design for these actuators. Thus the stepper motor approach was chosen.

There were many stepper motor manufacturers listed in the study. Of these, Faulhaber had the widest selection of small, lightweight motors and all were well documented with extensive specifications. The time allowed for this design did not permit accurate calculation of the required torque, so the smallest Faulhaber motor with the highest available gear ratio was chosen. While not ideal, this was a reasonable approach because zoom speed could later be traded for torque by using a higher gear ratio between the motor and cam. A two phase AM1020 series Faulhaber motor with the specifications in table VIII was chosen; for greater detail, refer to the component specification sheets enclosed at the end of this report.

TABLE VIII. Stepper motor characteristics

Characteristic	Value
Nominal Voltage	12V
Holding Torque	1.6 mNm
Maximum Holding Torque	2.4 mNm
Full Step Angle	18°
Shaft Bearings	Sintered Bronze
Mass	5.5 g
Maximum Diameter	10 +0.00 -0.07 mm

The AD CM M current mode drive circuitry was also purchased from Faulhaber and LabView code was written to interface with it. The motor arrived with a 64:1 reduction planetary gear head which reduced the full step size to approximately 0.28° and increased the holding torque to approximately 153 mN·m.

Drive Component Design

The motor is held in a bracket bolted to the housing (figures 43 and 44) and interfaces with the cam through two spur gears. An 8 tooth spur gear (SDP-SI P/N 1_AB_1MY05008) was press fitted onto the motor output shaft as delivered from the supplier. A 110 tooth spur gear (SDP-SI P/N S12N05M110A0310) was altered to remove the center so it could be press fitted onto the cam sleeve. Two holes were also drilled perpendicular to the front face 180° apart to accommodate dowel pins that would fix the gear to the cam sleeve and force the two to rotate together. Both are 20 pitch gears and together they yield a 13.75:1 reduction. With both gear reductions, approximately 16,000 motor steps are required for one complete zoom cycle. The theoretical stepper motor/drive train accuracy, even when backlash is included, is quite good.

The motor bracket can be fixed to the housing in any of six positions as determined by the pairs of threaded holes in the back of the housing. These different positions were made available to ensure that the motor could always be put in a position that would not interfere with the SWIR camera. In each position there are two screws that pass through the motor bracket and thread into the housing. One screw passes through a round hole and functions as a pivot, while the other passes through a curved slot. Before final tightening of the screws, this arrangement allows the user to pivot the motor toward or away from the large spur gear and "zero out" the backlash associated with meshing the two gears. It is desirable to have as little backlash as possible, because it translates directly into angular position error in the cam. Once the minimum backlash position has been achieved, both motor bracket screws can be tightened to maintain that position.

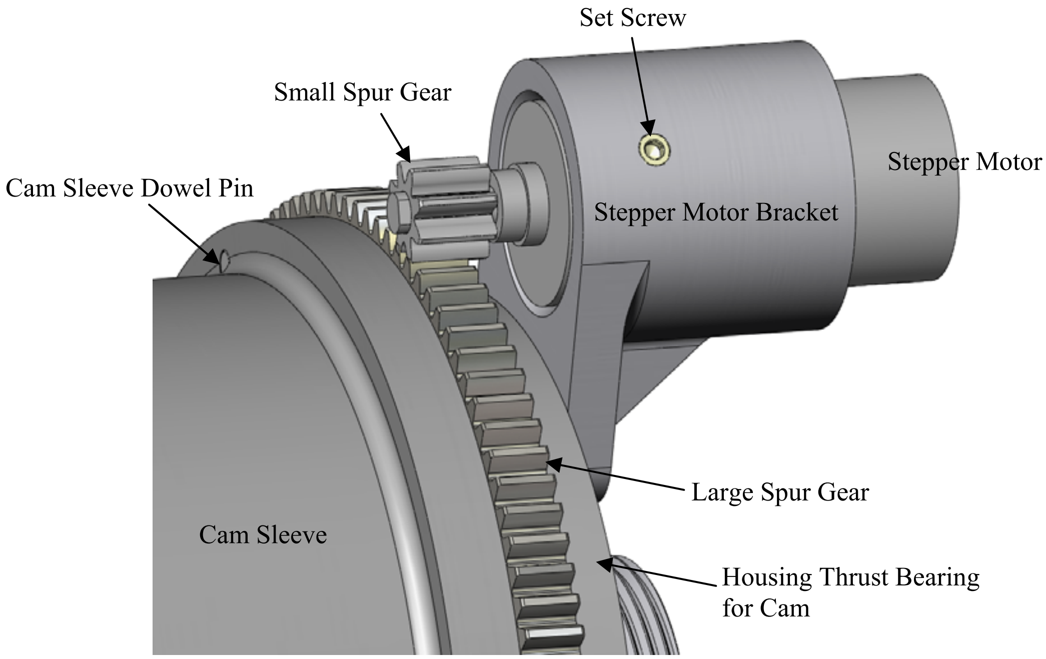


FIG 43 Stepper motor interface with cam.

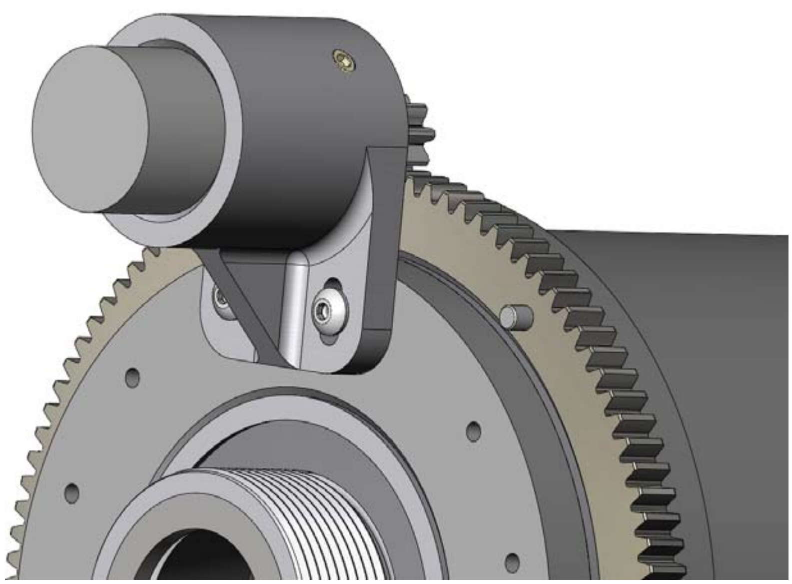


FIG 44 Attachment of stepper motor bracket to housing with backlash adjustment.

In order to design the pivot to accommodate a reasonable range of initial backlash values, it was necessary to develop expressions relating the screw separation R_1 and height of the bracket d to the change in distance between spur gears Δd. Using expressions 18 – 20 the necessary arc length and radius of the slot to produce a change in gear separation Δd can be determined. See figure 45 for an explanation of the parameters in expressions 18 – 20. Because the cam gear is so much larger than the motor gear, the lateral change in relative gear position *x* is assumed to be inconsequential.

$$s_1 = R_1\varphi \quad \text{and} \quad s_2 = R_2\varphi \rightarrow s_1 = \frac{R_1 s_2}{R_2} \qquad [18]$$

$$d = R_2 \sin\varphi \quad \text{and} \quad d' = R_2 \sin\varphi' \qquad [19]$$

$$\Delta d = d - d' \qquad [20]$$

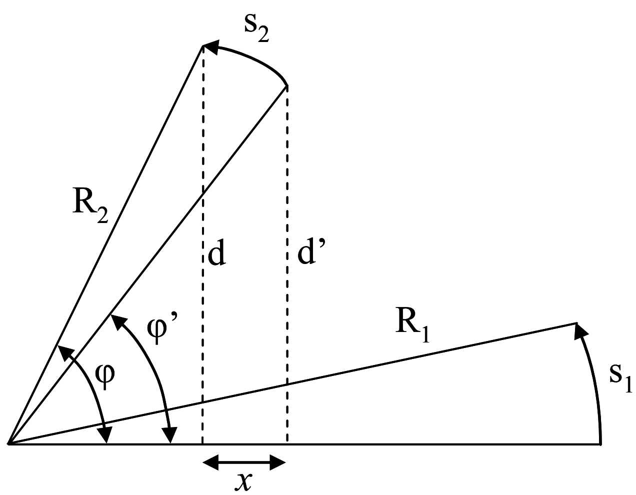


FIG 45 Geometry of the pivoting stepper motor bracket.

Additional features of the motor bracket include two set screws bearing on the motor case to hold it in place, a chamfer at each end to ease motor insertion and the use of a rib to provide strength with reduced weight.

Fabrication and Assembly

Most of the parts were fabricated by K. S. Machines in Cleveland, OH using CNC equipment reading from .stp files based on the SolidWorks models. SolidWorks drawings (.slddrw) and part files (.sldprt) were provided to the machinists so that parts could be fabricated by converting the part files into .stp files when appropriate. Cam slots were precisely specified by including polynomial expressions on the drawings describing slot geometry in terms of cam dimensions.

Tools for the fabrication process were designed and provided to the machinist with the part files. One such tool was intended for cam fabrication (figure 46). It consists of an aluminum cone and two halves of an aluminum cylinder with half conical sections removed from the central axis. These two half cylinder sections were mated at the flat surfaces and inserted inside the cam before the slots were cut. This assembly was then wedged onto the cone and tightened using a ½-20 machine bolt and large washer. The cone forced the two half cylinder sections apart and securely held the cam in place on a CNC mill while the slots were cut. This method prevented warping of the cam or uneven slot surfaces that could have come from the part yielding under the cutting tool. This technique was suggested by Michael Schuette in the NRL Tactical Electronic Warfare Division.

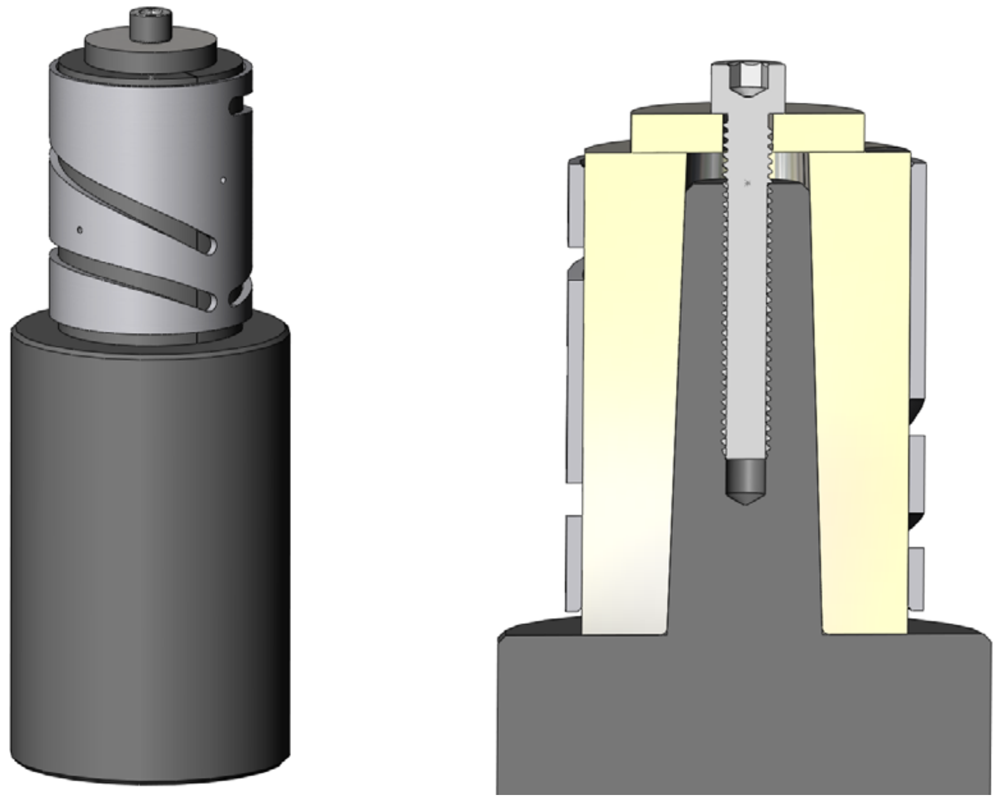


FIG 46 Tools for cutting cam slots.

Several tools were fabricated for use when assembling the zoom system. These included two spanner wrenches, a plug for mount 1 assembly, a gear blank to set the spacing for a real gear and a mandrel for cam/cam-sleeve integration. Step by step assembly instructions are listed in the following sections, followed by cross section illustrations of the fully assembled prototype in figures 47 and 48.

Cam, Cam Sleeve and Spur Gear

1. Slip the cam over the mandrel with the slot for mount 1 down.
2. Slip the 3.2mm thick gear blank over the cam cylinder until it rests on the shelf at the bottom of the mandrel
3. Slip the cam sleeve over the cam cylinder until it contacts the gear blank.
4. Rotate the cam sleeve until the pin holes on the cam sleeve and cam cylinder line up.
5. Press dowel pins (McMaster 91515A012) through holes until they stop at the mandrel.
6. Remove the cam cylinder/cam sleeve assembly from the mandrel.
7. Remove the gear blank from the mandrel.
8. Turn the cam cylinder/cam sleeve assembly over and put it back on the mandrel in the opposite orientation.
9. Press the gear (not gear blank) over the cam cylinder until it meets the ridge on the cam sleeve.
10. Rotate the gear until the holes in the gear and cam sleeve flange (thrust bearing) line up.
11. Remove the whole assembly from the mandrel, turn it over and put it back on the mandrel in the original orientation.
12. Press the dowel pins (McMaster 98515A008) through the cam sleeve and gear until they stop at the mandrel.
13. Remove the whole assembly from the mandrel.

Mount 1 with Lens 1

1. Insert the plug in mount 1.
2. Place appropriate thickness shims (if necessary) on the three flat sections of the mount where the guides will sit.

3. Place the first guide on a flat section with the wide side against the mount. Align the holes with those in the mount and insert two spring pins (McMaster P/N 92383A149).
4. Repeat step 3 for the other two guides.
5. Remove the plug and gently drop lens 1 into the mount, flat side first.
6. Use a spanner wrench to screw the retaining ring (chamfer side out) into the mount until it makes contact with the lens.

Mount 2 with Lenses 2 & 4 and the Aperture

1. Gently drop lens 4 into mount 2 part A and dab three small drops of epoxy on the edges of the lens at 120° intervals.
2. Gently drop lens 2 into mount 2 part B and dab three small drops of epoxy on the edges of the lens at 120° intervals.
3. Gently drop the aperture into the sliding lens assembly without the pin, snap ring side down. Line up the aperture so that the threaded pin hole will be accessible through the slot in part A.
4. Set the rubber annulus on the aperture.
5. Screw the part B into part A using the spanner wrench until it stops.
6. Place appropriate thickness shims (if necessary) on the three flat sections of the mount where the guides will sit.
7. Place the first guide on a flat section with the wide side against the mount. Align the holes with those in the mount and insert two spring pins (McMaster P/N 92383A149).
8. Repeat step 3 for the other two guides.

Mount 3 with Lenses 5 and 6

1. Place the retaining ring on a metal or plastic plate and set lens 6 on it in the center groove, convex side up.
2. Hold mount 3 above the lens and retaining ring, with the ledge for lens 6 facing down.
3. Carefully push the camera interface down over lens 6 and the retaining ring until the mount contacts lens 6.
4. Lift the mount, turn it over and put a SMALL drop of adhesive on the OUTSIDE of the junction between the mount and retaining ring to hold them in place.
5. Turn the mount back over and gently drop lens 5 onto the shelf on the opposite side of the camera interface, convex side up.
6. Rest the O-ring on the lens and adjacent to the mount inside diameter.
7. Put a SMALL drop of adhesive on the OUTSIDE of the junction between the mount and O-ring to hold them in place.

Installing the Mounts and Cam

1. Carefully begin threading mount 3 into the end of the housing. Using care not to cross-thread the parts, use a spanner wrench to screw the two parts together until they stop.
2. Slide mount 2 into the housing, with the guides sliding in the slots cut in the housing.
3. When the threaded aperture pin hole becomes visible through the pin slot on the housing, insert the aperture pin through the slot and screw it into the aperture using a flat head screw driver.
4. Slide mount 2 into the main barrel in the same manner.
5. Slip the cam/cam sleeve/spur gear assembly over the housing, gear end first. Press it on until it makes contact with the flange on the housing.
6. Align the two large (4.5mm dia) holes in the cam sleeve with the two guides that have three holes. This may require some adjustment of the mount positions and rotating the cam.
7. Press each of the two bearings onto a dowel pin (McMaster 91585A014) so that the pin is flush with the inner race of the bearing. Note: Do NOT apply force to the outer race along the center bore axis, it will destroy the bearing. Press on the inner race.
8. Insert the bearing/pin assemblies through the holes in the came sleeve and insert the pins in the center holes in the guides. Press lightly on the pins until the inner bearing races meet the raised square pads on the guides.
9. Insert plastic plugs in the holes in the cam sleeve.

Drive Components and Camera

1. Slip the left thrust bearing ring over the left end of the housing until it contacts the end of the cam.
2. Rotate the ring until the slots line up with the threaded holes in the housing.
3. Insert socket head cap screws (McMaster 92949A052) with washers (McMaster 98029A021) and tighten down, keeping very slight pressure on the ring so it stays in contact with the cam.
4. Screw the SWIR camera onto mount 3. Turn on the camera and examine the image.
5. Rotate entire assembly to thread it in/out of the camera housing to fine-tune the focus.
6. When focus is correct, measure the distance between the camera housing and flange on mount 3 with calipers and remove mount 3 from the camera.
7. Insert shims in the groove on mount 3 equal to the distance measured with the calipers.
8. Screw the entire assembly back onto the camera body until it stops. Focus should be correct.
9. Place the motor bracket against the back of the housing, with the hole and slot aligned with two of the holes in the housing. Choose the holes that are most convenient, given the camera orientation.
10. Screw two socket head cap screws (McMaster 92385A014) through the motor bracket and into the housing. Do not tighten all the way.
11. Slide the pinion onto the stepper motor shaft until it is flush with the end of the shaft. Put a SMALL drop of BLUE Loctite in the gap between the ID of the pinion and the flat on the stepper motor shaft.
12. Slip the stepper motor into the bracket and screw in two socket head set screws (McMaster 92949A054) against it. Do not tighten the screws.
13. Pivot the stepper bracket so the spur gear and pinion on the stepper motor mesh properly. Move the stepper in or out of the stepper bracket so the two faces of the gears are flush.
14. Tighten all screws until the fixture and motor are secure.

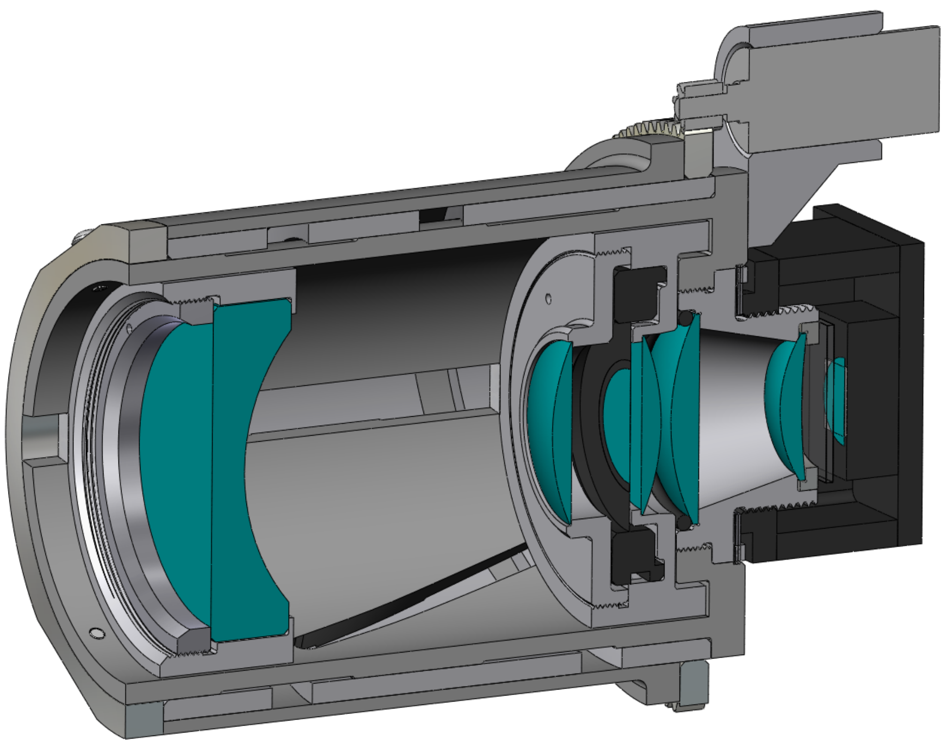


FIG 47 Cross section view of fully assembled prototype 3.4 in the zoomed out position.

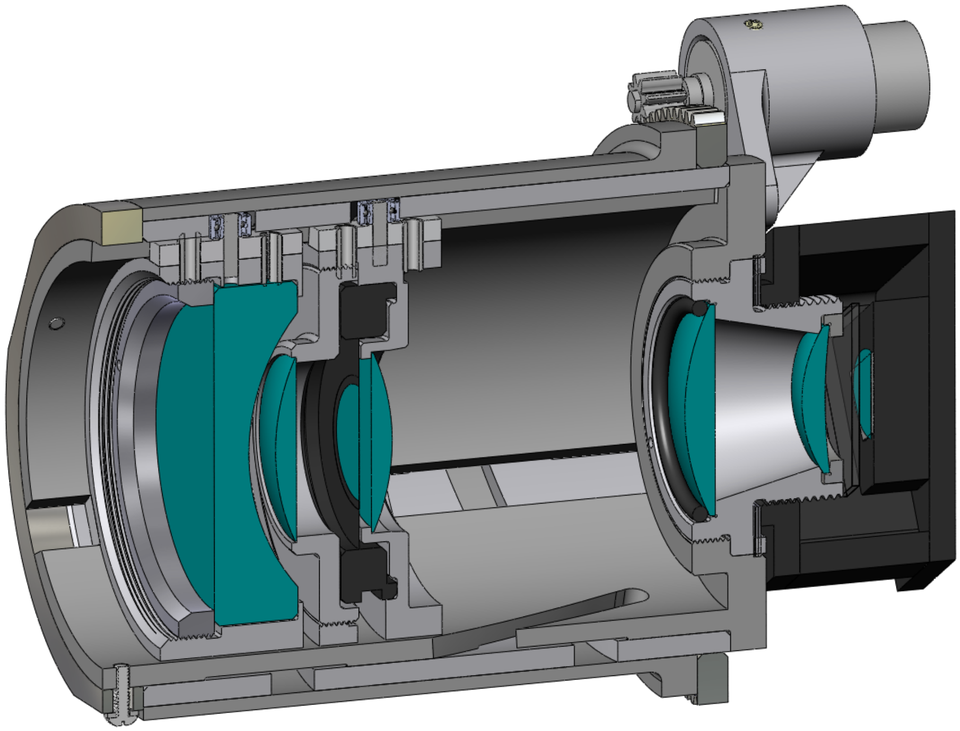


FIG 48 Cross section view of fully assembled prototype 3.4 in the zoomed in position, showing lens mount bearings and guides.

Results

Overall prototype 3.4 was a success. When the cam is driven, the lenses move correctly and produce a clear image that changes magnification. The f/# remains steady as the system zooms due to the aperture diameter changing in the proscribed manner. Many of the adjustments were found to work well, such as the cam thrust bearing pressure adjustment and BFL adjustment. The surface finishes reduce stray light and the Teflon impregnated parts demonstrate lower coefficients of friction. The system has not been subjected to temperature extremes, but in the course of ordinary use no impact of temperature on image quality has been observed. Comparisons to commercial systems of comparable zoom designed for use with SWIR cameras indicate that this system is smaller, lighter and has fewer optical elements.

The largest difficulty was the result of fabrication problems. The machine shop neglected to account for the anodization thickness and thus several parts were out of specified tolerances. As a result, the cam would not turn easily and mount 3 would not thread into the housing properly. Because of the concentricity requirements, the mount inside diameters for lenses 2 and 4 were quite close to the lens diameters. The unexpected anodization thickness prevented lens installation until the mounts were sanded. These parts required extensive work at NRL to force them to fit, and they never functioned as designed.

While team members worked closely in the development of prototype 3.4, greater coordination of future optical and mechanical designs would likely result in improved prototypes. One aspect of this design that would have benefited from greater interaction between the optical and mechanical engineers is the distance between the last lens (element 5) and the FPA. The optical designer was unaware of mechanical constraints on this parameter, and the mechanical engineer did not realize the design called for so small a separation until late in the design process. Accommodating this small separation in the mechanical design was a challenge; the final prototype consumed the entire allotted margin of safety in order to work properly.

There are several ways in which this design could be improved. For example, fewer components and critical dimensions where they must interface would reduce overall complexity and sensitivity to fabrication errors. This could come from the use of fewer optical elements, simpler lens motions, or more sophisticated mechanical designs. A custom-designed aperture integrated into the design would have been smaller and lighter than accommodating the COTS aperture used in prototype 3.4. A left hand thread on the camera adapter would have made fine tuning the BFL an easier process. The bearings could be replaced by simple Teflon pins in a design with less aggressive lens motions, without concern for the cam binding.

The program ended before the LabView code for stepper motor control could be completed, so the automatic zoom function has not been tested. To date the cam has only been rotated by hand, as if it were a manual telephoto lens.

The final mass of the zoom system was 192g, of which the lenses comprised 8g. The SWIR camera mass was 48g, for a total system mass of 240g. The zoom assembly length is approximately 65 mm, and the mean diameter is 53 mm. It is estimated by the designer that the zoom system mass could be reduced to approximately 75% of the current value by optimizing the mass of major components, such as the housing and cam. The length of the zoom assembly is determined by the optical design, but based on the performance of prototype 3.4, the diameter could be reduced by approximately 10% for this same optical design.

Other Designs

Prototype 1.0 (Stereo Lithography)

Prototype 1.0 (figure 49) was an early incarnation of the optical design used in prototype 2.0. It was the first prototype designed in SolidWorks (earlier versions had been drawn in AutoCAD) and largely a learning process. A desire to build the prototype quickly and utilize state of the art technology drove the decision to use stereo-lithography to fabricate the parts. The solid model (.stl) files were sent to ProtoCAD (La Plata, MD) and direct written in a UV cured photo resin.

This prototype performed poorly for several reasons. First, despite being dyed black, the photo-resin used to fabricate the parts was transparent to SWIR light. This caused significant contrast control problems and badly eroded the modulation transfer function (MTF) of the optics. The geometric tolerances for the parts were too large, so several parts would not slide as intended.

The team conclusion from this experience was that STL parts work well for design validation and demonstration models, but should not be used for working prototypes. The lessons learned from prototype 1.0 in terms of part design were incorporated into prototype 2.0.

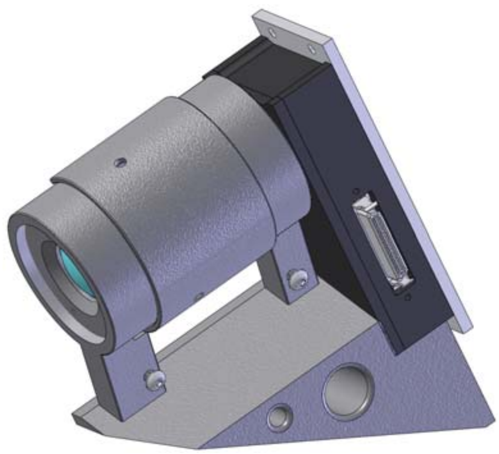


FIG 49 Rendered view of prototype 1.0

Prototype 2.3 (Non-actuated independently compressible tunable GRINs)

Problems with the tunable GRIN lenses inspired the design of prototype 2.3, which was a proof-of-concept lens assembly used in the laboratory and sponsor demonstrations. To work properly, the zoom strategy employed by prototype 2.0 relied on two identical tunable GRIN lenses with not only the same relaxed focal lengths, but the same deformation properties. CWRU was unable to produce two tunable GRIN lenses with identical spring constants and deformation properties, so devices using this zoom strategy tended to loose focus as they zoomed. The solution was to build a prototype in which the compression of each lens was controlled independently. This way the lenses could be compressed to different extents to account for variations in their properties.

The optical design for prototype 2.3 was similar to that of prototype 2.0 in that it also had three fixed focal length lenses and two tunable GRIN lenses. While the tunable GRIN lenses were the same, the fixed focal length lenses were changed to lessen the reliance on the tunable GRIN lenses for system performance. All five of the lenses were fabricated by CWRU.

The mechanical design (see figures 50 and 51) consists of three housings, the first of which contains mounts for lenses 1 and 2. The second housing contains the first tunable GRIN (lens 3) and a threaded disc that can be rotated to change the level of lens compression. The third housing contains the aperture, the second tunable GRIN (lens 4) and lens 5. A second threaded disc controls the level of lens 4 compression.

Each of the housings can be screwed into the next and locked in place with a threaded ring. This allows researchers to vary lens spacing to account for fabrication variation in the tunable GRIN lenses. The aperture is threaded and its position can be changed by threading it in/out of the third housing with a spanner wrench, and locking it in place with a threaded ring. The camera interface can be screwed into or out of the third housing to adjust the BFL.

CWRU was unable to machine lenses to the required physical tolerances, so a system was developed to correct deviations. Before final assembly, the lenses were cemented into aluminum rings using a jig to ensure that the rings were concentric with the optical axis of each lens, and the ring edges were perpendicular to the optical axis. The mounts were designed to accommodate these rings and hold them in the locations specified by the optical design, rather than relying on the lens dimensions.

All of the zoom assembly parts were fabricated by K.S. Machines (Cleveland, OH). The housings, lock rings and aperture are made of 6061-T6 aluminum and were not anodized because they were needed immediately for a demonstration. Later black paint was applied to the interior of the aluminum parts. All other parts are made of black Delrin.

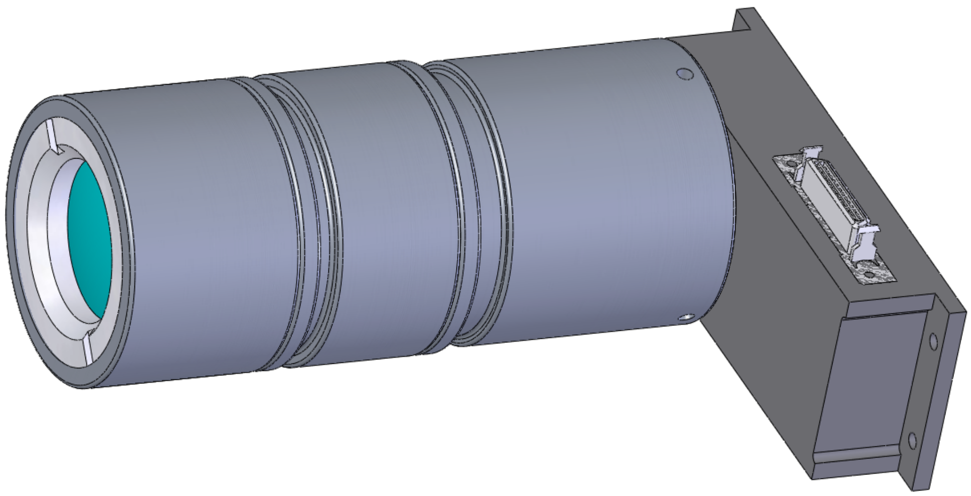


FIG 50 Rendered view of prototype 2.3

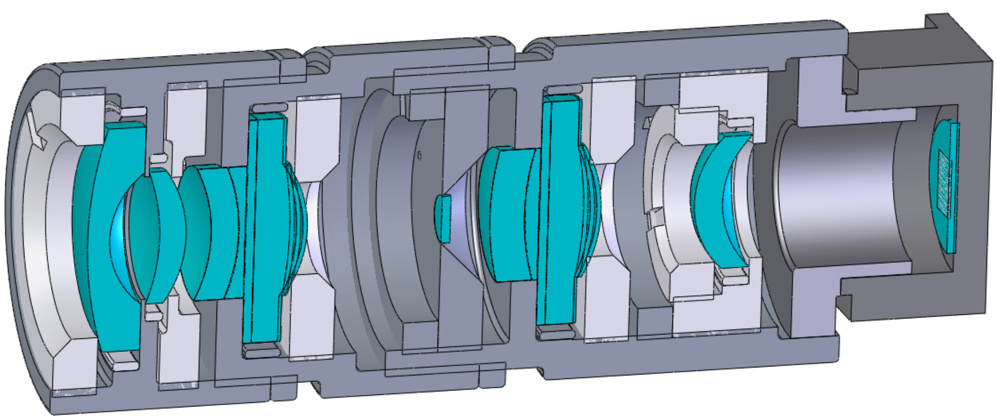


FIG 51 Cross section view of prototype 2.3

Prototype 2.5 (Actuated independently compressible tunable GRINs)

Prototype 2.5 is the fully automated version of prototype 2.3. The design was completed and shop drawings were produced, but it was never built. The optical designers concluded that the tunable GRIN

lenses would not have sufficient optical power to achieve the desired 3X zoom and the design was abandoned.
This zoom assembly (figures 52 and 53) uses the same lenses, lens spacing and adjustments as prototype 2.3. It is complex largely because so much adjustment was retained from the prototype 2.3 design. The spacing between the two tunable GRIN lenses is adjusted by the screw surrounded by a spring. The screw passes through unthreaded holes in both brackets and ends at a nylon lock nut. When the nut is tightened, the brackets are pulled together and the lens spacing decreases. When the nut is loosened, the spring pushes the two brackets apart and the lens spacing increases. The BFL is adjusted by rotating a collar at the right end of the assembly. As the collar rotates it screws toward or away from housing C. When it moves toward housing C it pushes on the camera adapter, compresses the Bellville washer springs pulls the FPA toward the housing to reduce the BFL. When the collar moves away from the housing, the FPA is pushed away from the housing by the Bellville washer springs. This design was chosen because it allows the user to adjust the BFL without changing the camera orientation with respect to the zoom assembly; in most other designs, one or the other must rotate. The distances between lenses 2 & 3 and 3 & 4 are adjustable by screwing the threaded housings into one another. The distance between lenses 4 & 5 is adjusted by screwing the mount for lens 5 further into housing C. The aperture position between the two tunable GRIN lenses can be adjusted by screwing it into or out of housing B.

The tunable GRIN lenses are compressed by two Faulhaber AM1020 stepper motors, one for each lens. The stepper motors drive ACME threaded rods which push or pull brackets connected through slots in the housings to the lens mounts. The brackets have commercial ACME threaded nuts into which the threaded rods are inserted. The threaded rods are connected to the stepper motor output shafts by Delrin collars with a set screw that bears against the flat on the output shaft. The lens compression force is borne by the Delrin collar pressing on a plate bolted to the motor bracket. This relieves the motor rotor of axial stress that would be beyond the manufacturer’s specifications and quickly wear out the motor bearings. The surface of the plate is coated with Teflon tape to reduce the friction load on the stepper motor.

The stepper motors each rest in a semi-circular trough in the motor bracket, cushioned by a thin strip of rubber. The motors are held in place by brackets that are screwed down onto the motor through rubber bushings. The rubber strip and bushings allow the user to adjust the clamping force on the motor until it is sufficient to prevent it from rotating.

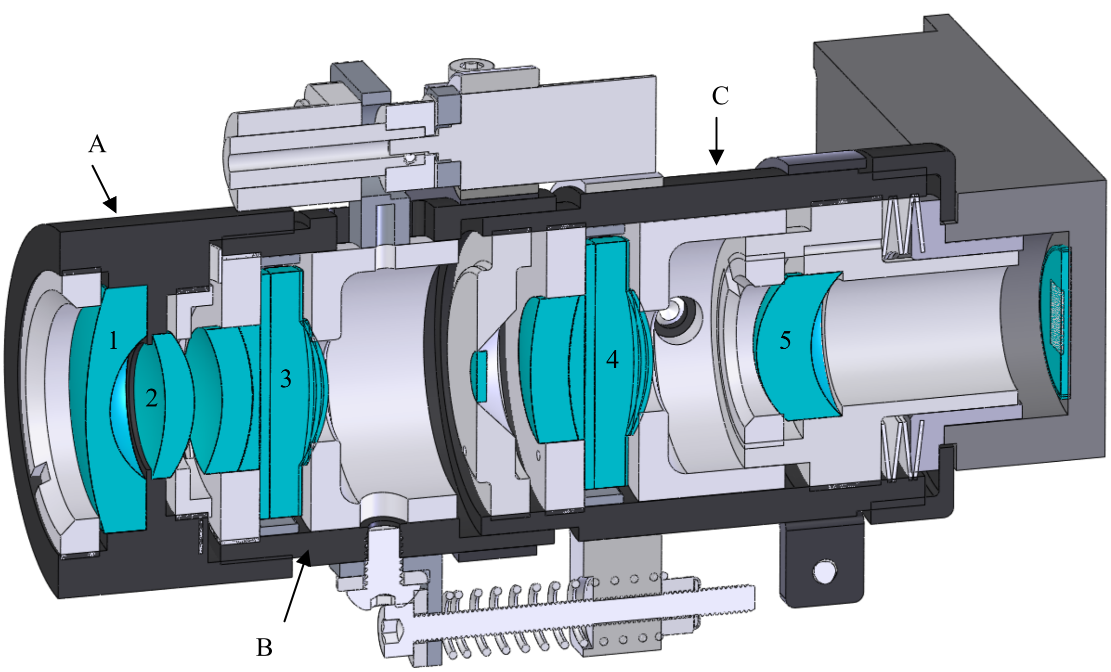


FIG 52 Cross section view of prototype 2.5

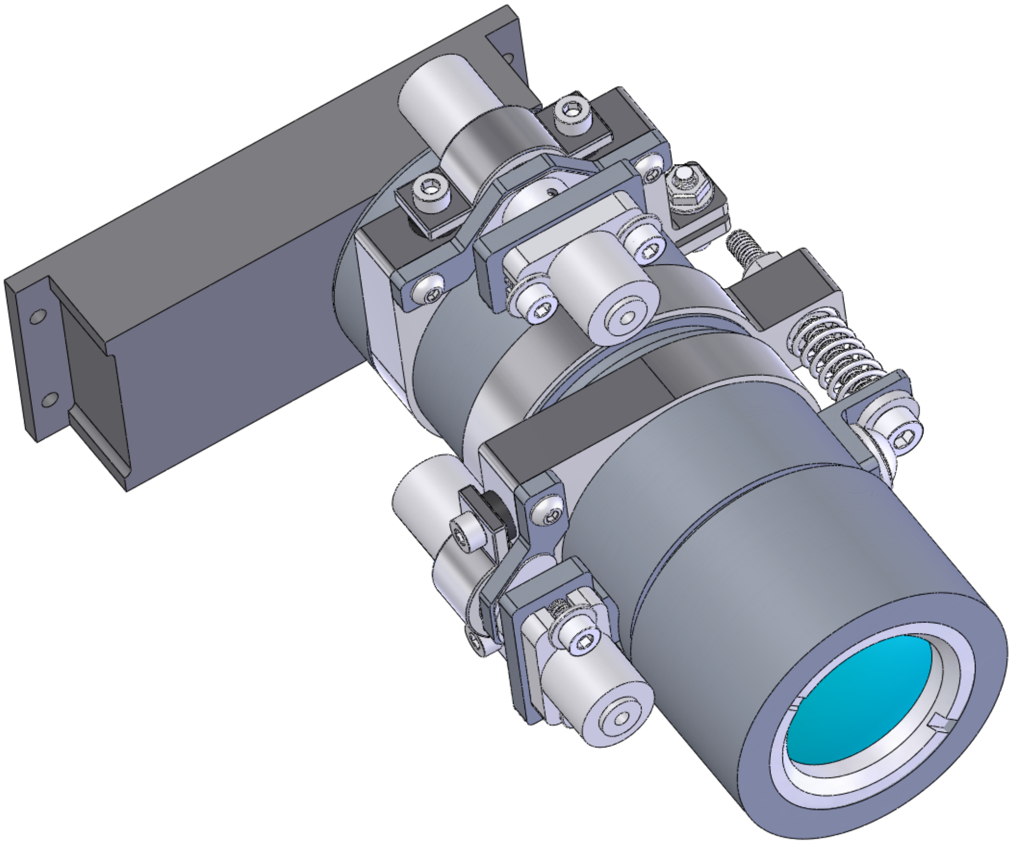


FIG 53 Rendered view of prototype 2.5

Lens Compressor for use with Profilometer

It became clear early in the program that it would be necessary to accurately characterize the surface profiles of the tunable GRIN lenses. An optical profilometer of the same type commonly found in optometrists' offices was purchased to map the lens surfaces, and a simple device for compressing tunable GRIN lenses was built (figure 54). The device was designed to compress the lens in small increments so that the profilometer could map the surface at each increment. This would yield data describing the lens surface profile as a function of lens compression.

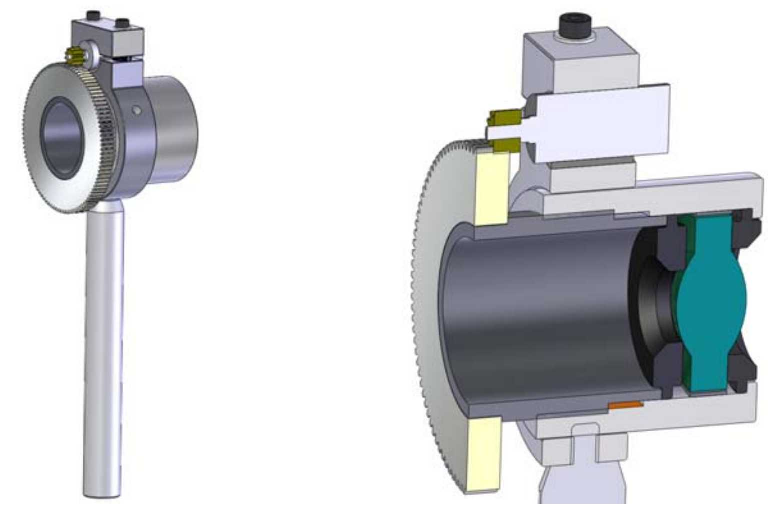


FIG 54 Rendered view (a) and cross section (b) of lens compressor for use with profilometer.

The Faulhaber AM1020 stepper motor drives a pinion, which drives a spur gear pressed onto a large cylinder. The cylinder rotates inside the fixture. The cylinder has external threads, and the fixture has internal threads. As the cylinder rotates, it screws into the fixture and compresses the lens. The motor is retained by a bracket and two socket head cap screws. The fixture has a threaded hole that mounts to a standard optical table post. The rear aperture provides the profilometer with access to the lens surface. The fixture position along the optical axis can be adjusted and fixed in place by a set screw.

Summary

Five complete zoom systems were designed by NRL code 6110 for the BOSS program; three were built and tested. Of the three systems that were built, two compressed tunable GRIN lenses to generate the change in magnification, while the third relied on moving lenses along the optical axis. One tunable GRIN system was flown on a UAV.

The tunable GRIN lenses show promise as an alternative to traditional fixed focal length optics, and mechanical systems have been developed for them. The simplicity of these systems is a major advantage over competing zoom lens designs, and the work here suggests that more compact, lighter weight mechanical designs could be developed to take advantage of tunable GRINs. In order to be useful in fielded systems however, there are several lens fabrication and material problems that must be resolved. Most importantly, the fabrication of nearly identical lenses with higher indices of refraction (greater optical power) is necessary.

The fixed focal length GRIN lenses have been demonstrated to work well in prototype 3.4. This device yields clear images at variable magnification from 1-3X. It is considerably lighter and smaller than commercially available SWIR zoom lenses and there is significant room for further improvement. In particular, an optical design utilizing only GRIN lenses with aspheric surfaces would likely be smaller and require fewer elements. This would lead to a major reduction in the mass and size of the mechanical components required to mount the lenses and drive the zoom feature. There are also portions of prototype 3.4 with the current optical design that are ripe for optimization. The primary focus when designing prototype 3.4 was to build a working prototype, not optimize it.

References

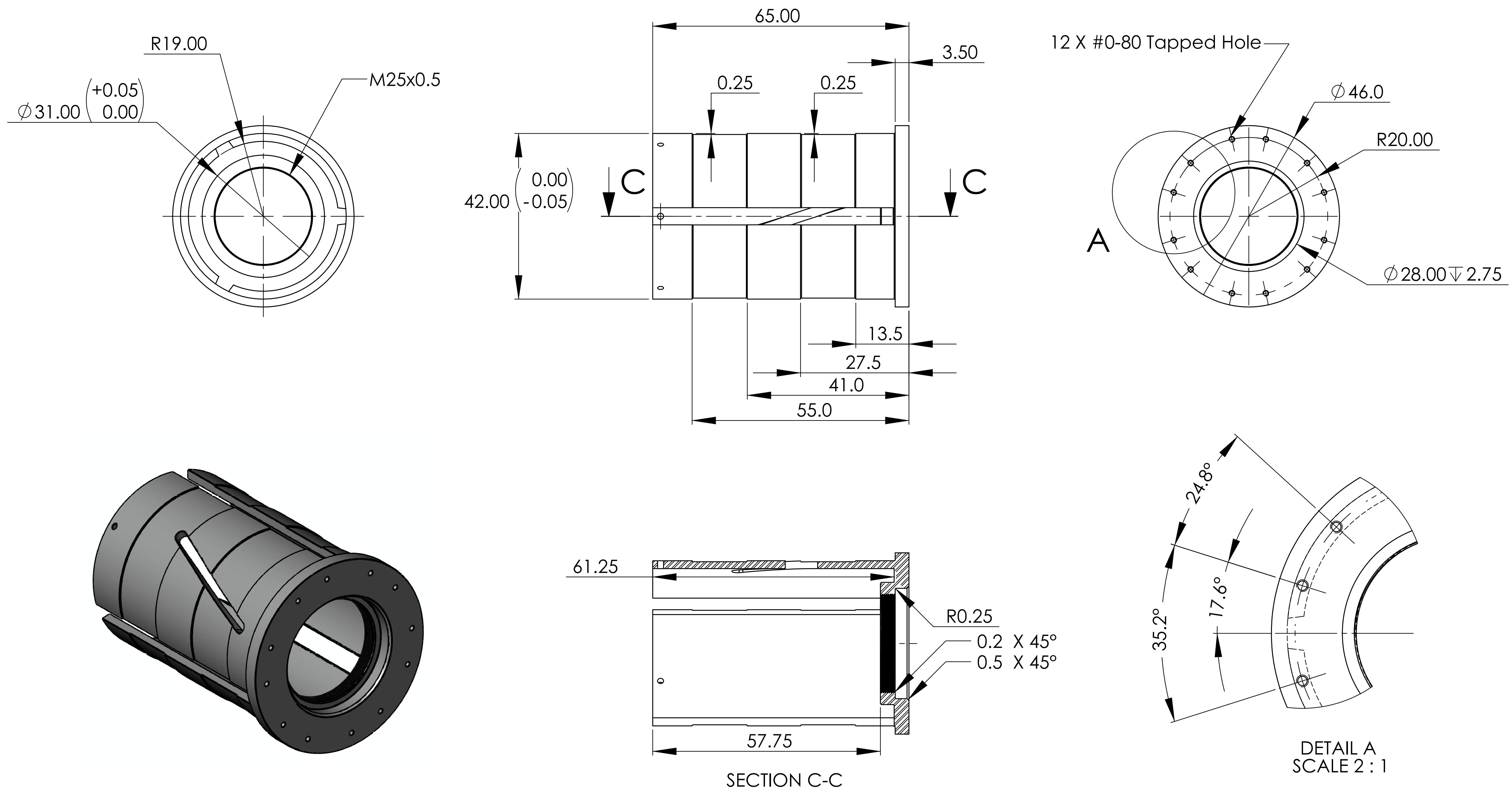
1. http://www.darpa.mil/dso/thrusts/bio/biologically/boss/index.htm
2. Hecht, Eugene. *Optics*. 3rd ed. Reading, MA: Addison-Wesley, 1998.
3. Jin, Y., H. Tai, A. Hiltner, E. Baer, and James S. Shirk. "New Class of Bioinspired Lenses with a Gradient Refractive Index." *Journal of Applied Polymer Science* 103 (2007): pp 1834-1841.
4. Stroman, Richard O. *Actuator Trade-Off Analysis for DARPA/BOSS Prototype II*. NRL/MR/6110-06-9009; MR-9009. Washington, DC: Naval Research Laboratory, 2006.
5. Sandrock, Marie. "Lens Data." Group Meeting. Case Western Reserve University, Cleveland, OH. 10 Mar. 2005.
6. Oberg, Erik, Franklin D. Jones, Holbrook L. Horton, and Henry H. Ryffel. *Machinery's Handbook*. 27th ed. New York: Industrial Press Inc., 2004. pp 2188-2213.
7. Acarnley, Paul P. *Stepping Motors: a Guide to Theory and Practice*. 4th ed. London: The Institution of Electrical Engineers, 2002.
8. Yoder, Jr., P.R. *Optical Mounts: Lenses, Windows, Small Mirrors, and Prisms*. Optomechanical Engineering Handbook, Ed. Anees Ahmad, Boca Raton: CRC Press LLC, 1999.
9. Yoder Jr., Paul R. *Mounting Lenses in Optical Instruments*. Bellingham, WA: SPIE Optical Engineering Press, 1995. p 13.

Acknowledgements

The author gratefully acknowledges DARPA DSO for funding this work and supporting efforts to continue it. This mechanical design work would have been meaningless without the scientists and engineers in NRL Optical Sciences and the CWRU Macromolecular Science Department who designed, built and analyzed the optics. At NRL they include James Shirk, Marie Sandrock, Michael Wiggins, Guy Beadie, Erin Fleet, and Richard Lepkowicz. At CWRU they include Prof. Eric Baer, Prof. Anne Hiltner, Michael Ponting, Yi Jin, Aditya Ranade, Huiwen Tai, and Jiong Yu. Mechanical design suggestions from Michael Schuette in the NRL Tactical Electronic Warfare Division were also helpful.

Design Documentation

Prototype 3.4 Part, Assembly and Tool Drawings



THIS PART MATES TO:
BOSS-P3-6 (FITS OVER THIS PART)
BOSS-P3-8 (THREADS INTO THIS PART)
BOSS-P3-9 (SLIDES IN ONE OF THE SLOTS IN THIS PART)
BOSS-P3-10 (SLIDES IN ONE OF THE SLOTS IN THIS PART)
BOSS-P3-11 (HELD ONTO THIS PART BY THREE SCREWS)
BOSS-P3-12 (HELD ONTO THIS PART BY TWO SCREWS)
BOSS-P3-13 (SLIDES IN ONE OF THE SLOTS IN THIS PART)
BOSS-P3-14 (SLIDES IN ONE OF THE SLOTS IN THIS PART)

MASK THREADS AND SLOTS
BEFORE GLASS BEAD

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm
TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL
6061-T6 ALUMINUM

FINISH
GLASS BEAD, HARD COAT ANODIZE (TYPE III),
DYED BLACK, TEFLON IMPREGNATED

	NAME	DATE
DRAWN	STROMAN	10.02.06
CHECKED	STROMAN	10.02.06
ENG APPR.	STROMAN	10.02.06

PROJECT
DARPA BOSS

ASSEMBLY
Prototype 3

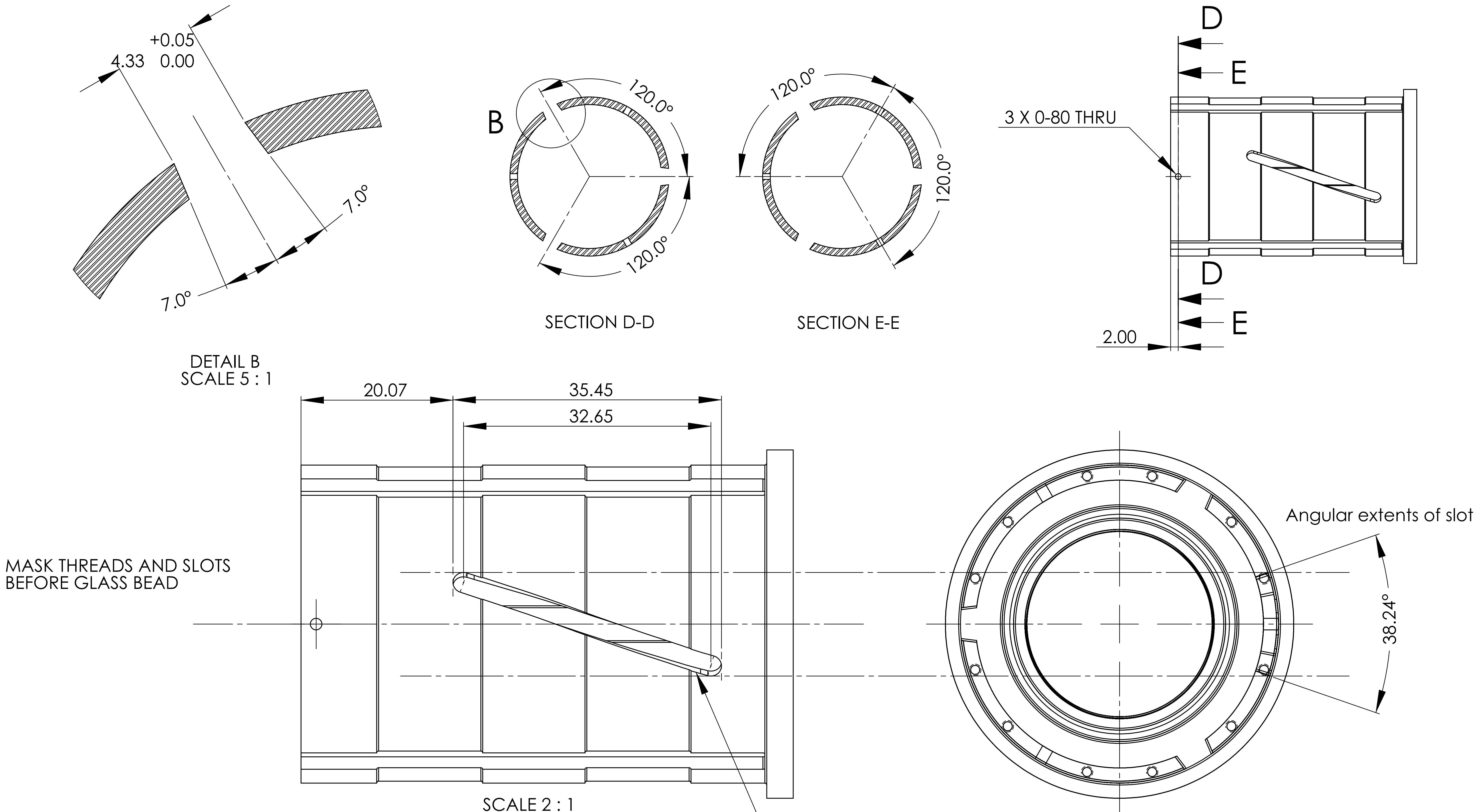
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME
Main Housing

PART NO.
BOSS-P3-1

SIZE B | DWG. NO. BOSS-P3-1 | REV. 1.2

SCALE:1:1 | MASS: 47.33g | SHEET 1 OF 2



THIS PART MATES TO:
BOSS-P3-6 (FITS OVER THIS PART)
BOSS-P3-8 (THREADS INTO THIS PART)
BOSS-P3-9 (SLIDES IN ONE OF THE SLOTS IN THIS PART)
BOSS-P3-10 (SLIDES IN ONE OF THE SLOTS IN THIS PART)
BOSS-P3-11 (HELD ONTO THIS PART BY THREE SCREWS)
BOSS-P3-12 (HELD ONTO THIS PART BY TWO SCREWS)
BOSS-P3-13 (SLIDES IN ONE OF THE SLOTS IN THIS PART)
BOSS-P3-14 (SLIDES IN ONE OF THE SLOTS IN THIS PART)

SEE SOLIDWORKS MODEL FOR
SLOT SPECIFICATIONS AND LOCATION

SLOT WIDTH 2.80mm

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL
6061-T6 ALUMINUM

FINISH
GLASS BEAD, HARD COAT ANODIZE (TYPE III), DYED BLACK, TEFLON IMPREGNATED

	NAME	DATE
DRAWN	STROMAN	10.02.06
CHECKED	STROMAN	10.02.06
ENG APPR.	STROMAN	10.02.06

PROJECT
DARPA BOSS

ASSEMBLY
Prototype 3

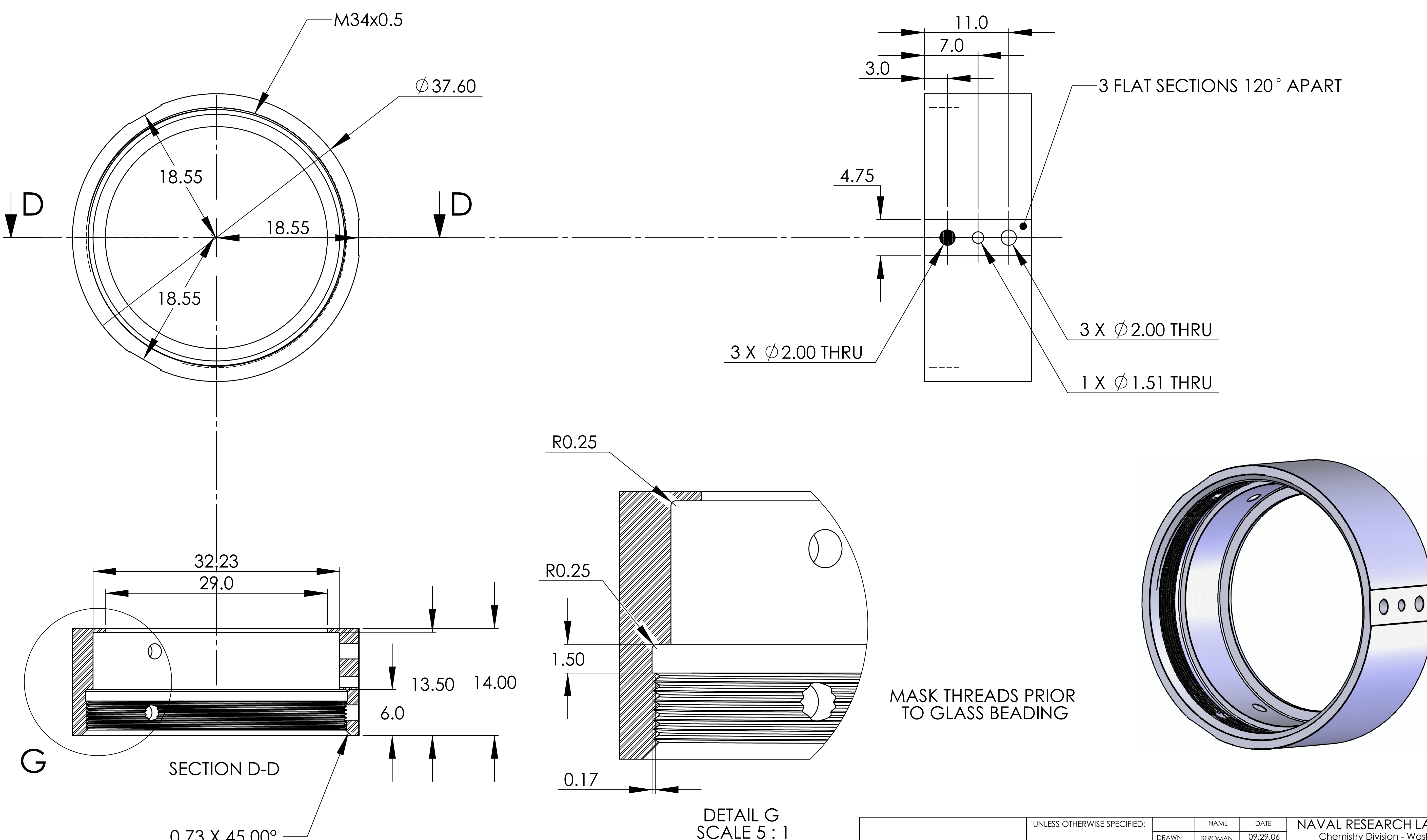
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME
Main Barrel

PART NO.
BOSS-P3-1

SIZE	DWG. NO.	REV.
B	BOSS-P3-1	1.1

SCALE:1:1 MASS: 47.33g SHEET 2 OF 2



MASK THREADS PRIOR
TO GLASS BEADING

ALL DIMENSIONS AFTER ANODIZATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 5 DEG
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL
6061-T6 Aluminum

FINISH
GLASS BEAD, HARD COAT ANODIZE (TYPE III),
DYED BLACK

	NAME	DATE
DRAWN	STROMAN	09.29.06
CHECKED	STROMAN	09.29.06
ENG APPR.	STROMAN	09.29.06

PROJECT
DARPA BOSS

ASSEMBLY
Prototype III

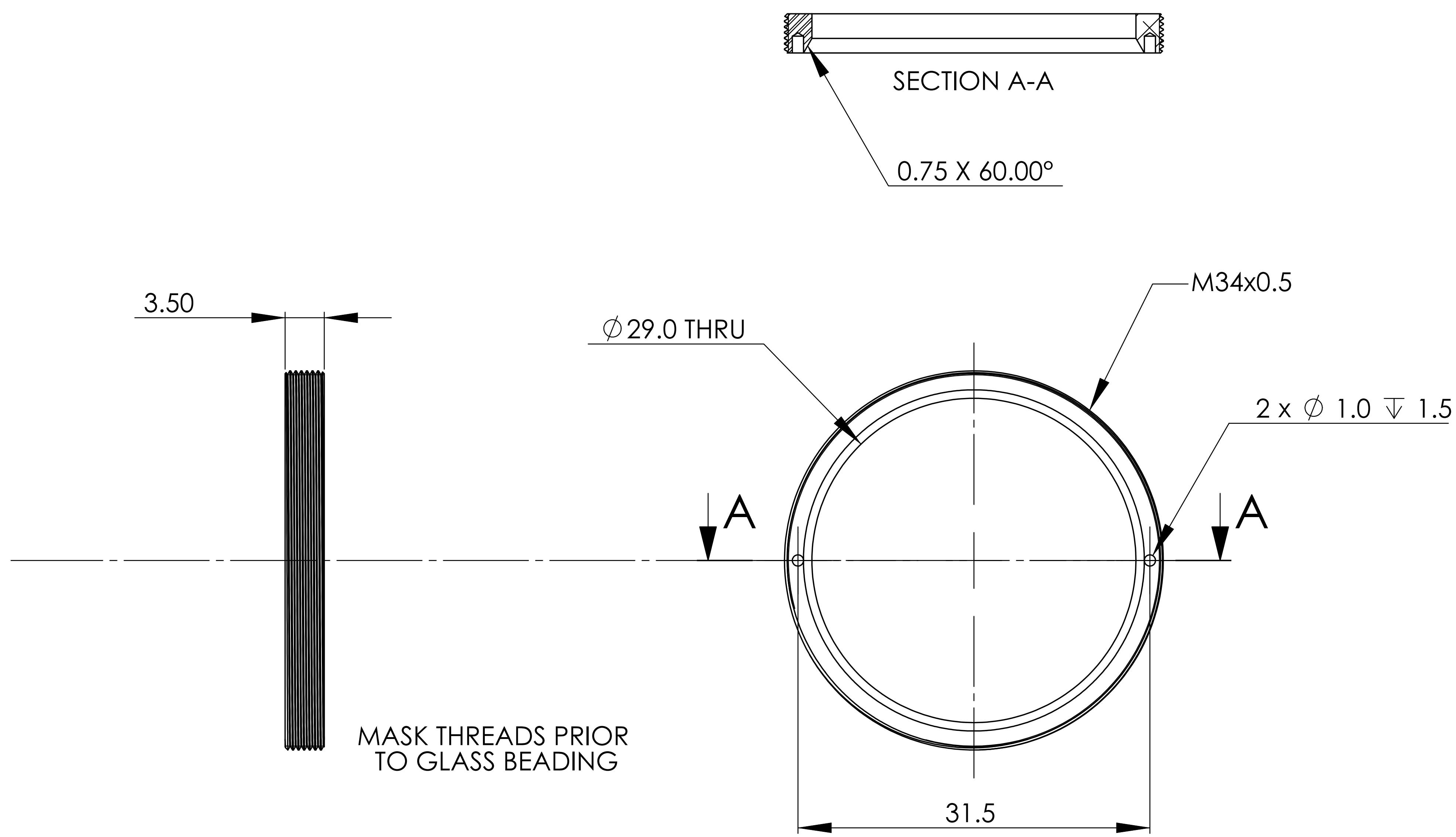
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME
Mount 1

PART NO.
BOSS-P3-2

SIZE	DWG. NO.	REV.
B	BOSS-P3-2	1.0

SCALE:2:1 MASS: 10.30g SHEET 1 OF 1



THIS PART MATES TO:
BOSS-P3-2 (THIS RING THREADS INTO PART BOSS-P3-2)

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL: 6061-T6 Aluminum

FINISH: GLASS BEAD, HARD COAT ANODIZE (TYPE III), DYED BLACK

	NAME	DATE
DRAWN	STROMAN	10.02.06
CHECKED	STROMAN	10.02.06
ENG APPR.	STROMAN	10.02.06

PROJECT: DARPA BOSS

ASSEMBLY: Prototype 3

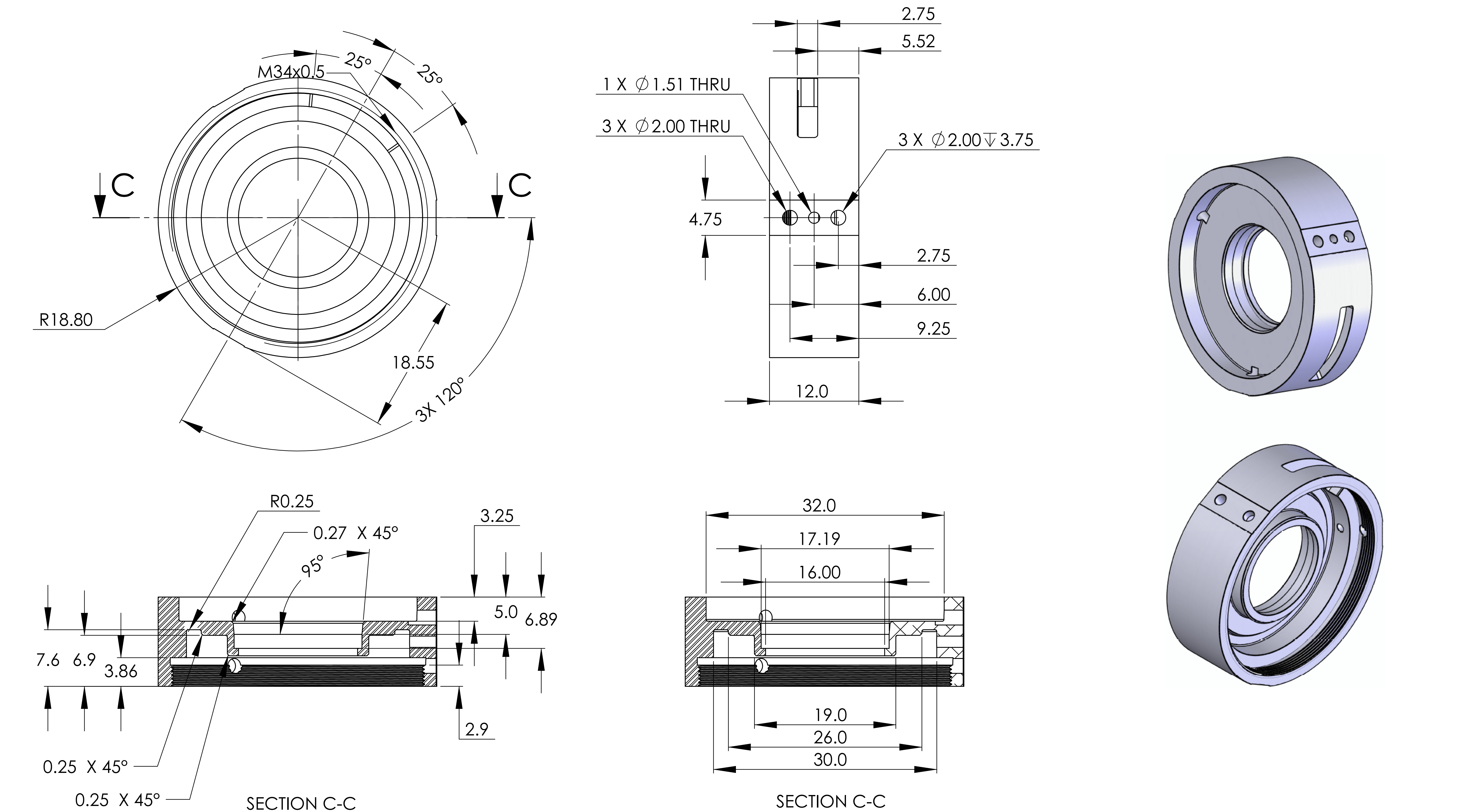
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME: Lens #1 Retaining Ring

PART NO.: BOSS-P3-3

SIZE: B | DWG. NO.: BOSS-P3-3 | REV.: 1.0

SCALE: 2:1 | MASS: 1.45g | SHEET 1 OF 1



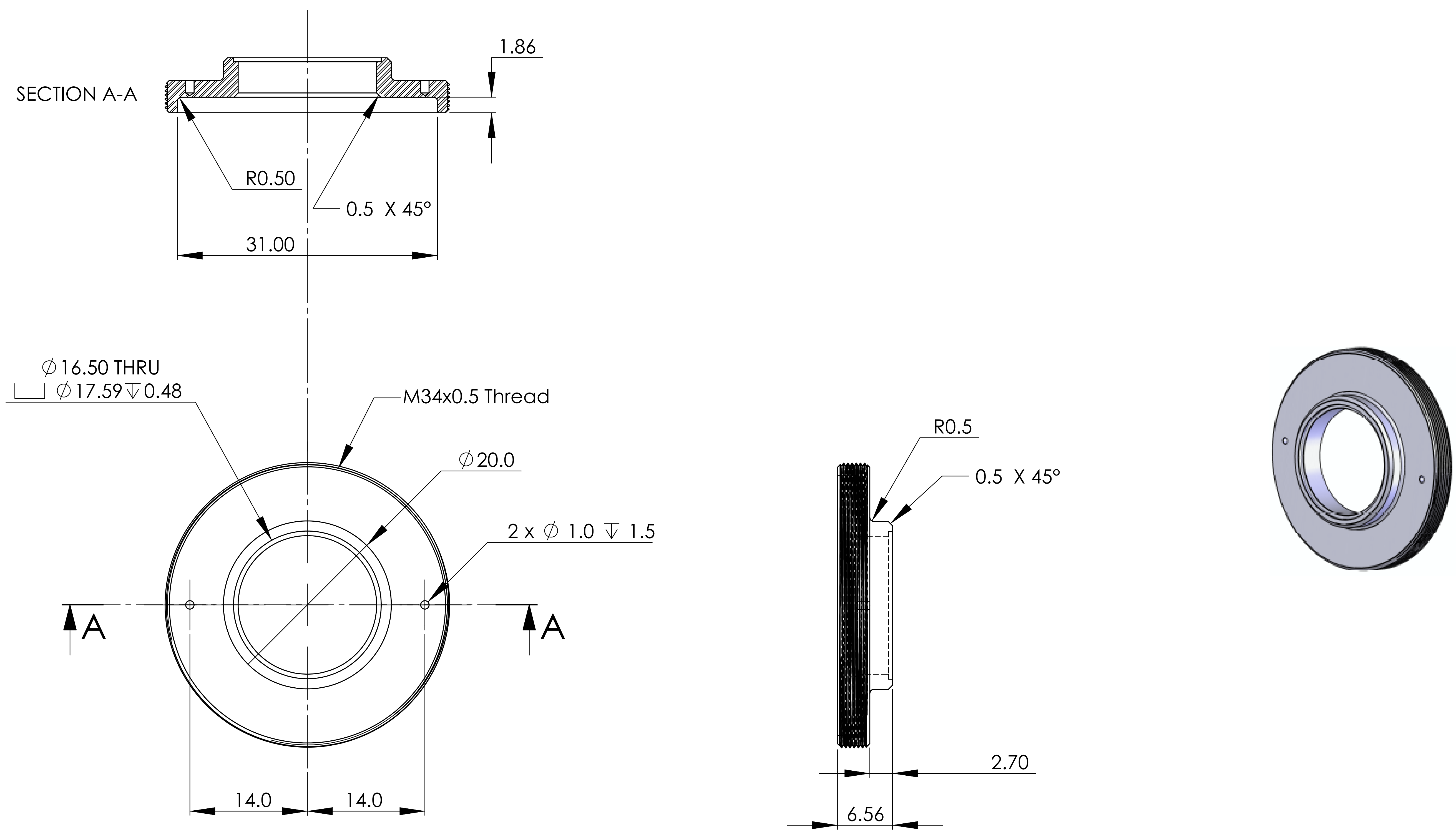
THIS PART MATES TO:
BOSS-P3-5 (THREADS INTO THIS PART)
BOSS-P3-13 (PINNED TO TWO OF THE FLATS ON THIS PART)
BOSS-P3-14 (PINNED TO ONE OF THE FLATS ON THIS PART)

MASK THREADS PRIOR TO GLASS BEAD
ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 5 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	10.02.06
	CHECKED	STROMAN	10.02.06
	ENG APPR.	STROMAN	10.02.06
MATERIAL: 6061-T6 Aluminum	PROJECT: DARPA BOSS		
FINISH: GLASS BEAD, HARD COAT ANODIZE (TYPE III), DYED BLACK	ASSEMBLY: Prototype 3		

NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME	Mount 2 Part A
PART NO.	BOSS-P3-4
SIZE	B
DWG. NO.	BOSS-P3-4
REV.	1.0
SCALE	2:1
MASS	13.38g
SHEET	1 OF 1



THIS PART MATES TO:
BOSS-P3-4 (THIS RING THREADS INTO PART BOSS-P3-4)

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	10.02.06
	CHECKED	STROMAN	10.02.06
	ENG APPR.	STROMAN	10.02.06
MATERIAL 6061-T6 Aluminum	PROJECT DARPA BOSS		
FINISH GLASS BEAD, HARD COAT ANODIZE (TYPE III,) DYED BLACK	ASSEMBLY Prototype 3		

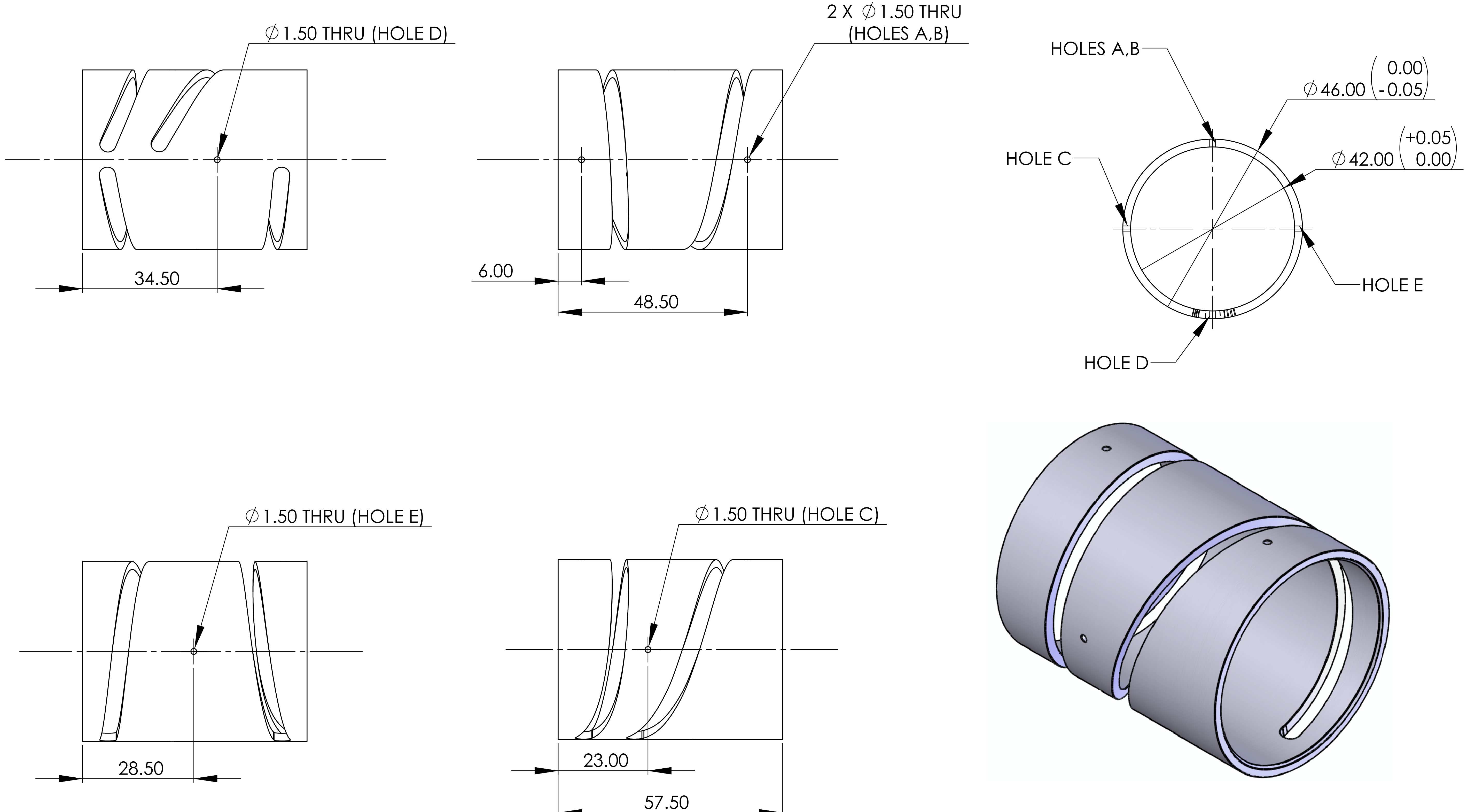
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME: Mount 2, Part B

PART NO.: BOSS-P3-5

SIZE: B | DWG. NO.: BOSS-P3-5 | REV.: 1.0

SCALE:2:1 | MASS: 4.93g | SHEET 1 OF 1



THIS PART MATES TO:
BOSS-P3-1 (SLIPS INSIDE THIS PART)
BOSS-P3-7 (PINNED TO THIS PART)
BOSS-P3-17 (PRESSED OVER THIS PART)

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL
6061-T6 ALUMINUM

FINISH
GLASS BEAD, HARD COAT ANODIZE (TYPE III), DYED BLACK, TEFLON IMPREGNATED

	NAME	DATE
DRAWN	STROMAN	10.05.06
CHECKED	STROMAN	10.05.06
ENG APPR.	STROMAN	10.05.06

PROJECT
DARPA BOSS

ASSEMBLY
Prototype 3

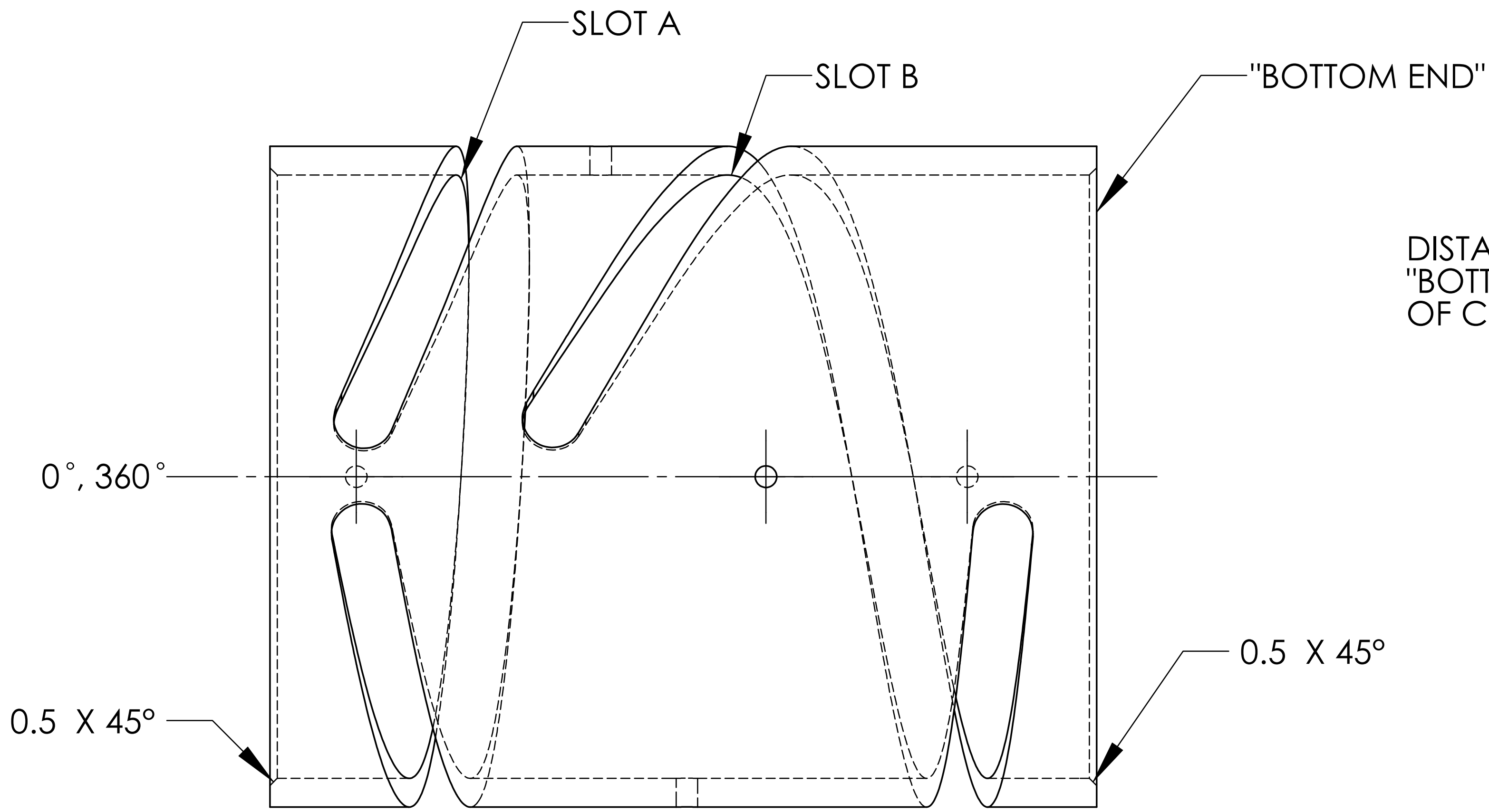
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME
Cam Cylinder

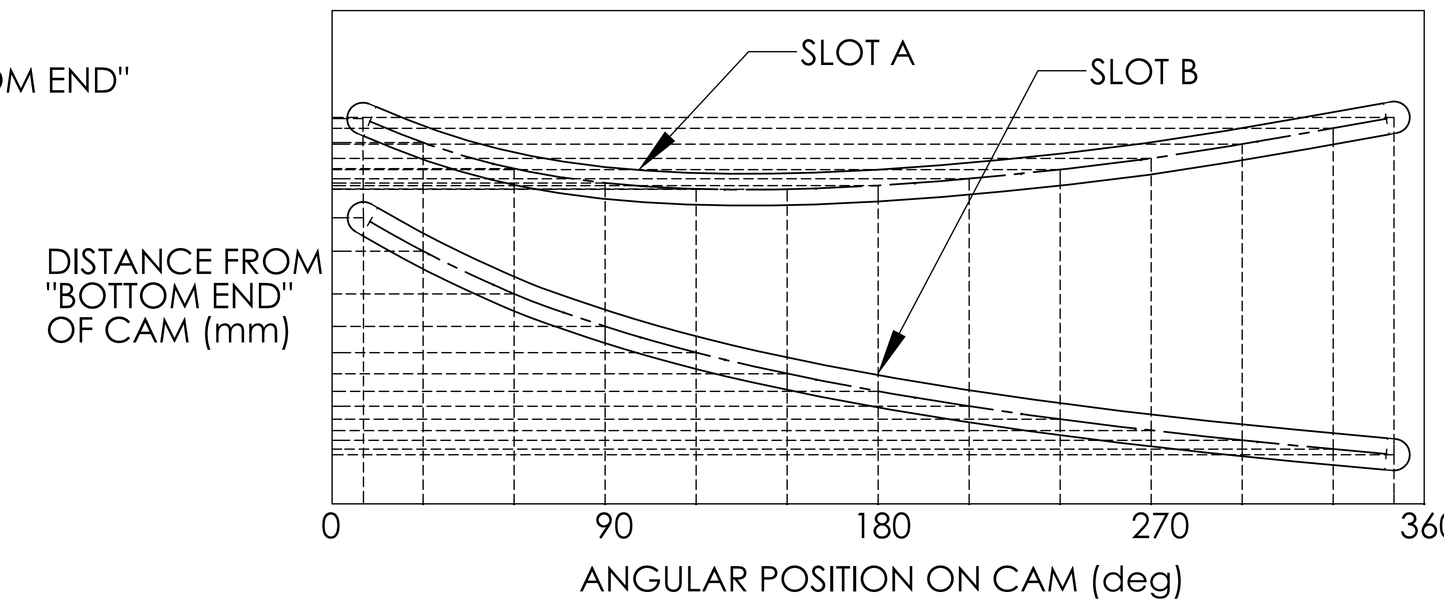
PART NO.
BOSS-P3-6

SIZE B | DWG. NO. BOSS-P3-6 | REV. 1.0

SCALE:1:1 | MASS: 36.57g | SHEET 1 OF 2



SCALE 2:1



ANGLULAR POSITION (deg)	SLOT A DISTANCE FROM "BOTTOM END" (mm)	SLOT B DISTANCE FROM "BOTTOM END" (mm)
10.3 (end)	50.97	37.85
30	47.79	33.43
60	44.35	27.78
90	42.45	23.48
120	41.66	20.01
150	41.62	17.22
180	42.11	14.89
210	43.02	12.91
240	44.22	11.20
270	45.70	9.71
300	47.59	8.40
330	49.69	7.24
349.7 (end)	51.13	6.51

NOTE: THESE POSITIONS DESCRIBE THE CENTER OF THE SLOT. THE 4.20mm THICKNESS OF THE SLOT AND 2.10mm RADIUS OF ENDS MUST BE ADDED.

SEE SOLIDWORKS PART FILE "CAM CYLINDER.SLDPRT" FOR DETAILS

SLOT A DISTANCE (mm) FROM "BOTTOM END" OF CAM AS FUNCTION OF ANGLE (deg)

$$D(a) = 0.0000007a^3 + 0.0008a^2 - 0.1708a + 52.272$$

SLOT B DISTANCE (mm) FROM "BOTTOM END" OF CAM AS FUNCTION OF ANGLE (deg)

$$D(a) = 0.0000008a^3 + 0.0007a^2 - 0.2361a + 39.960$$

SLOT THICKNESS AND POSITION ACCURACY ±0.03mm

THIS PART MATES TO:
BOSS-P3-1 (SLIPS INSIDE THIS PART)
BOSS-P3-7 (PINNED TO THIS PART)
BOSS-P3-17 (PRESSED OVER THIS PART)

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm
TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL
6061-T6 ALUMINUM

FINISH
GLASS BEAD, HARD COAT ANODIZE (TYPE III), DYED BLACK, TEFLON IMPREGNATED

	NAME	DATE
DRAWN	STROMAN	10.05.06
CHECKED	STROMAN	10.05.06
ENG APPR.	STROMAN	10.05.06

PROJECT
DARPA BOSS

ASSEMBLY
Prototype 3

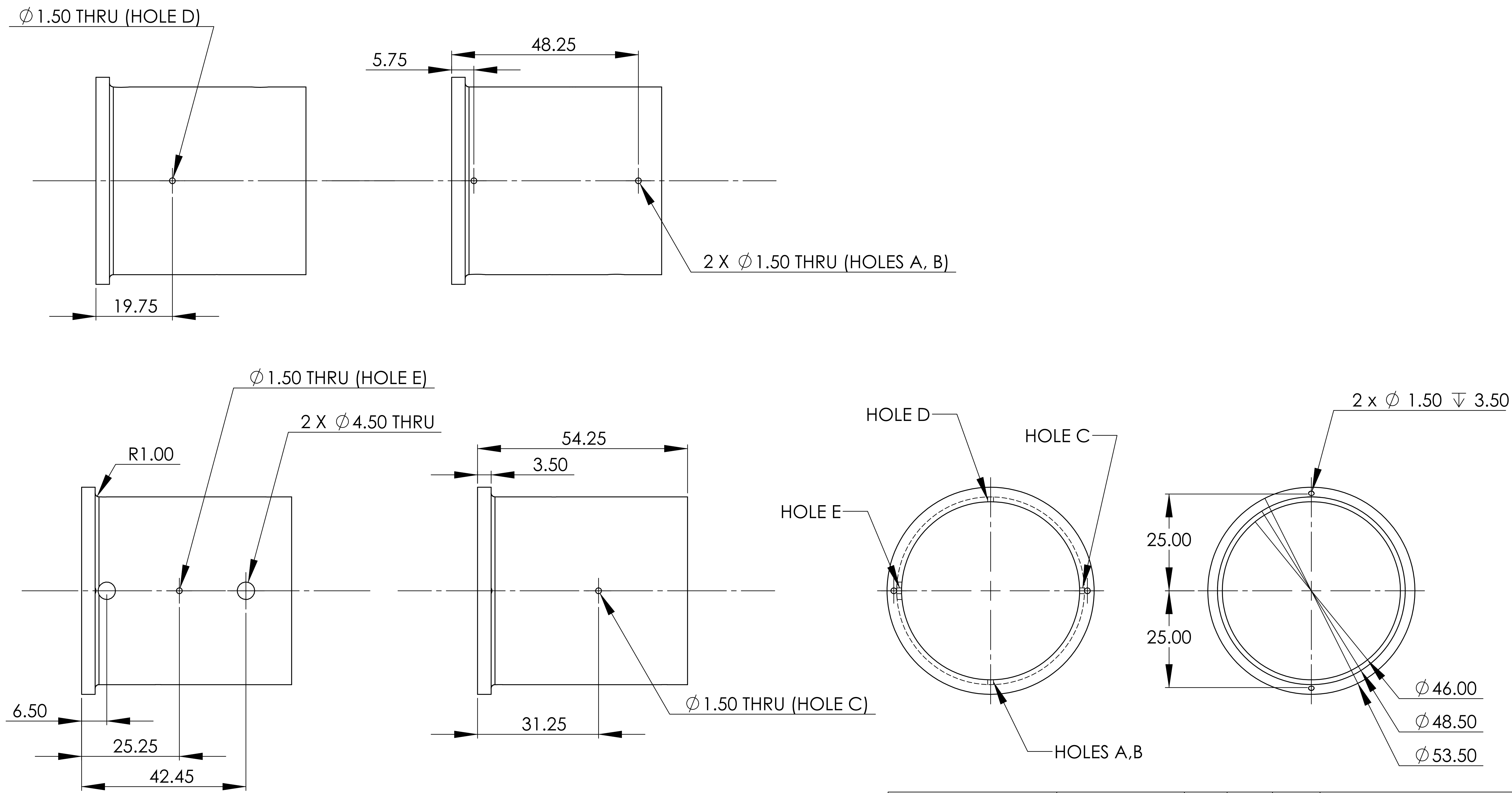
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME
Cam Cylinder

PART NO.
BOSS-P3-6

SIZE B | DWG. NO. BOSS-P3-6 | REV. 1.0

SCALE:1:1 | MASS: 36.57g | SHEET 2 OF 2



THIS PART MATES TO:
BOSS-P3-6 (PINNED TO THIS PART)
BOSS-P3-16 (PINNED TO THIS PART)

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL
6061-T6 ALUMINUM

FINISH
GLASS BEAD, HARD COAT ANODIZE (TYPE III),
DYED BLACK, TEFLON IMPREGNATED

	NAME	DATE
DRAWN	STROMAN	10.02.06
CHECKED	STROMAN	10.02.06
ENG APPR.	STROMAN	10.02.06

PROJECT
DARPA BOSS

ASSEMBLY
Prototype 3

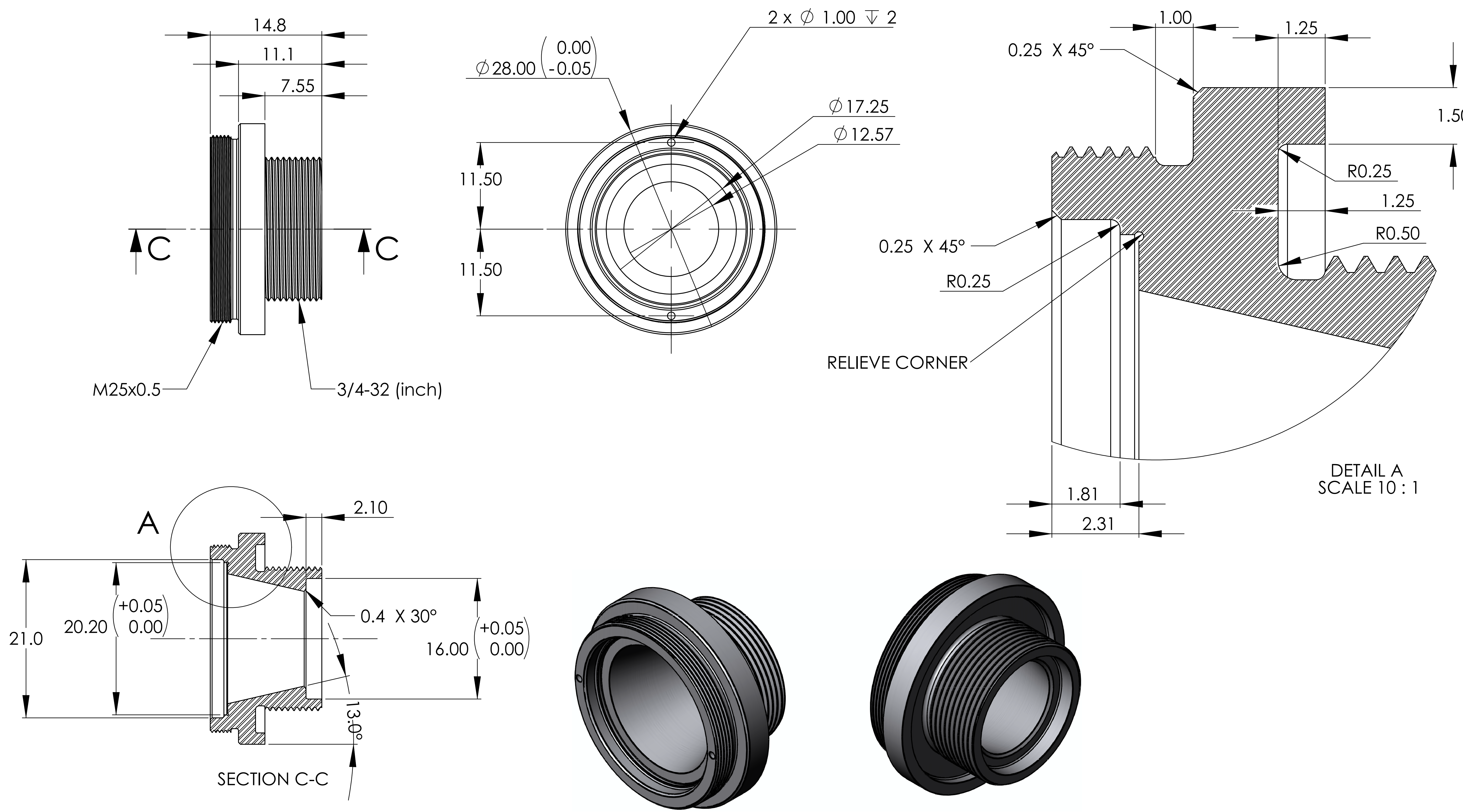
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME
Cam Cylinder Sleeve

PART NO.
BOSS-P3-7

SIZE B | DWG. NO. BOSS-P3-7 | REV. 1.0

SCALE:1:1 | MASS: 30.88g | SHEET 1 OF 1



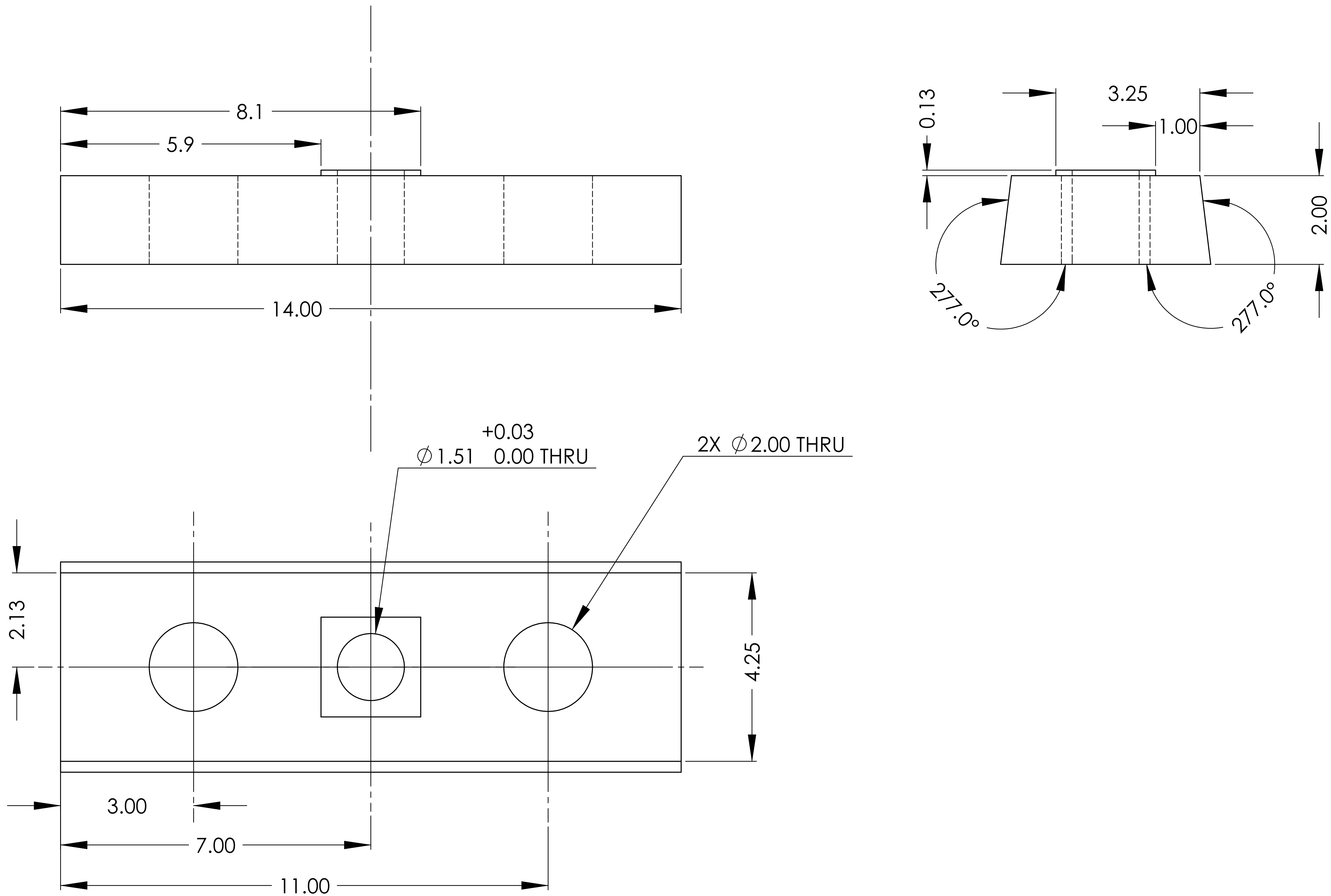
THIS PART MATES TO:
BOSS-P3-1 (THIS PART THREADS INTO BOSS-P3-1)
BOSS-P3-9 (PRESSES INTO THIS PART TO RETAIN LENS)
BOSS-P3-20 (THIS PART THREADS INTO BOSS-P3-20, SWIR CAMERA)

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	10.02.06
	CHECKED	STROMAN	10.02.06
	ENG APPR.	STROMAN	10.02.06
MATERIAL: 6061-T6 ALUMINUM	PROJECT: DARPA BOSS		
FINISH: GLASS BEAD, HARD COAT ANODIZE (TYPE III), DYED BLACK	ASSEMBLY: Prototype 3		

NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

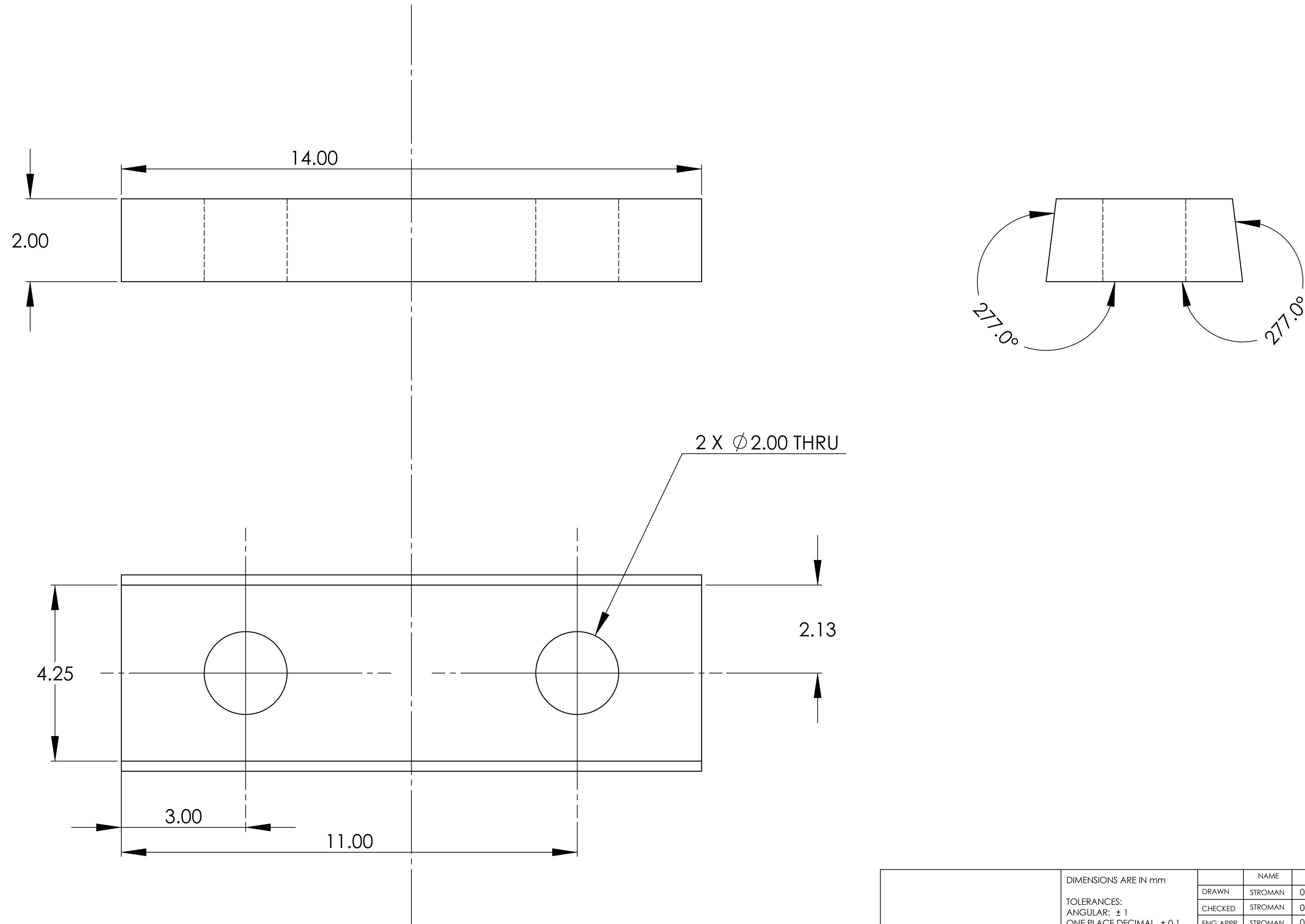
PART NAME	Mount 3
PART NO.	BOSS-P3-8
SIZE	B
DWG. NO.	BOSS-P3-8
REV.	1.0
SCALE	2:1
MASS	7.03g
SHEET	1 OF 1



THIS PART MATES TO:
BOSS-P3-2 (PINNED TO THIS PART)

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	09.29.06
	CHECKED	STROMAN	09.29.06
	ENG APPR.	STROMAN	09.29.06
MATERIAL BLACK DELRIN	PROJECT DARPA BOSS		
FINISH	ASSEMBLY Prototype 3		

NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC			
PART NAME Mount 1 Guide with Bearing			
PART NO. BOSS-P3-9			
SIZE B	DWG. NO. BOSS-P3-9		REV. 1.0
SCALE:5:1	MASS: 0.14g		SHEET 1 OF 1



THIS PART MATES TO:
BOSS-P3-2 (PINNED TO THIS PART)

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	09.29.06
	CHECKED	STROMAN	09.29.06
	ENG APPR.	STROMAN	09.29.06
MATERIAL BLACK DELRIN	PROJECT DARPA BOSS		
FINISH	ASSEMBLY Prototype 3		

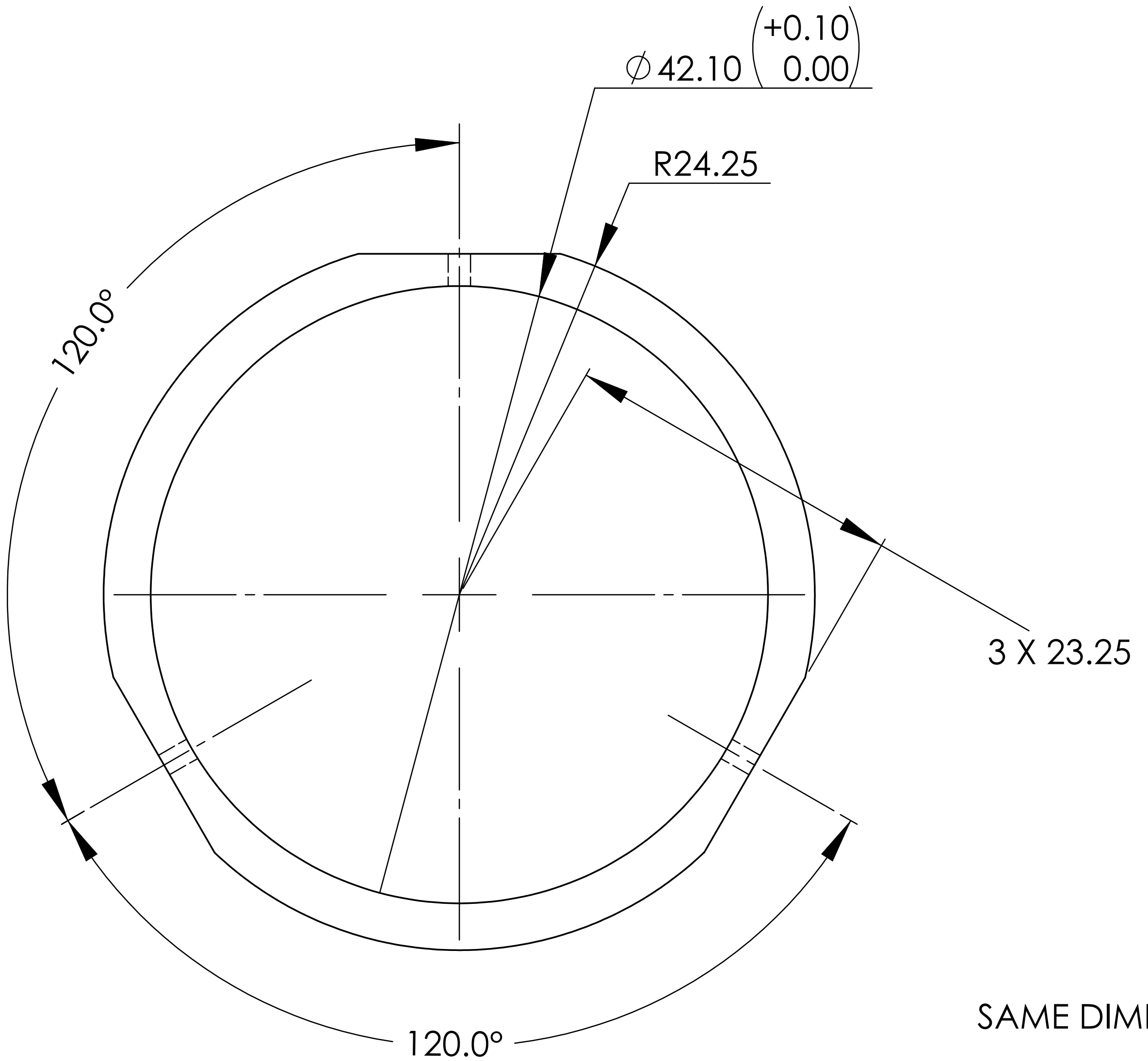
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

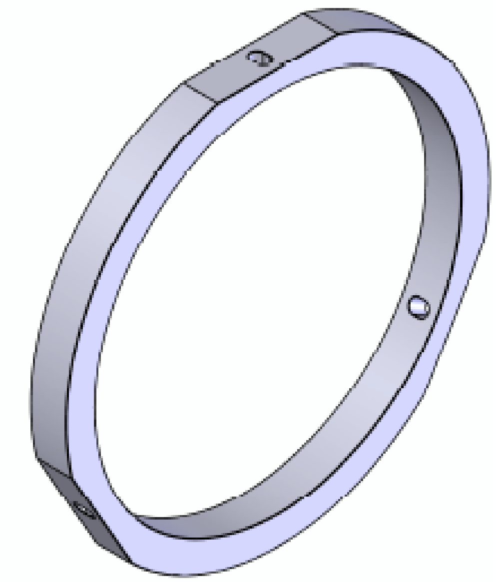
PART NAME Mount 1 Guide

PART NO. BOSS-P3-10

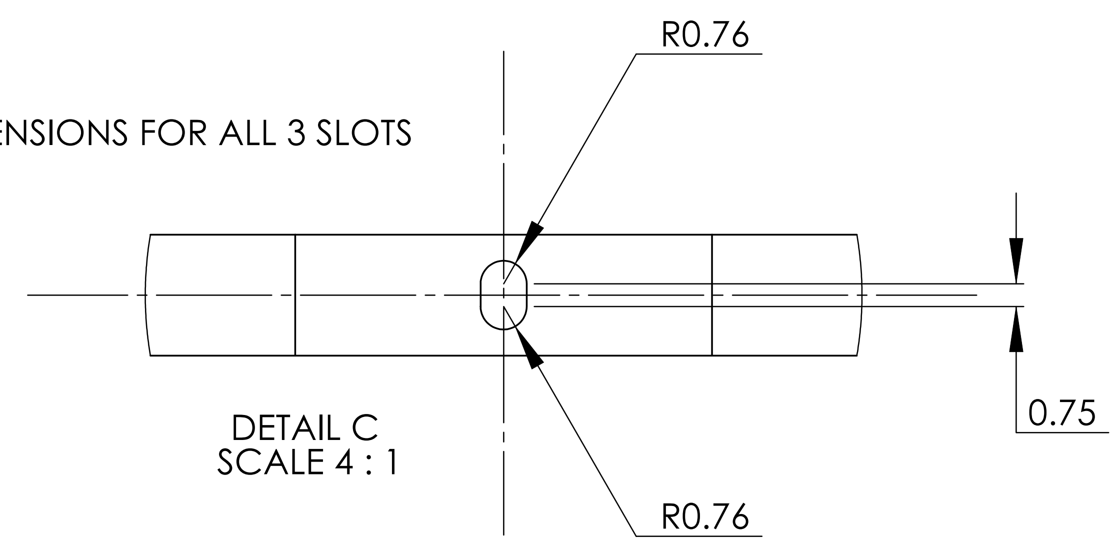
SIZE	DWG. NO.	REV.
B	BOSS-P3-10	1.0

SCALE:5:1 | MASS: 0.14g | SHEET 1 OF 1

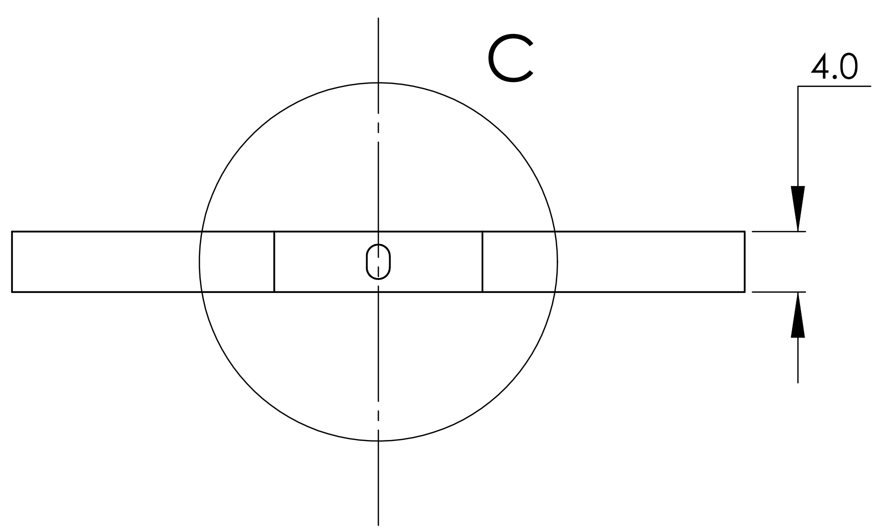




SAME DIMENSIONS FOR ALL 3 SLOTS



DETAIL C
SCALE 4 : 1



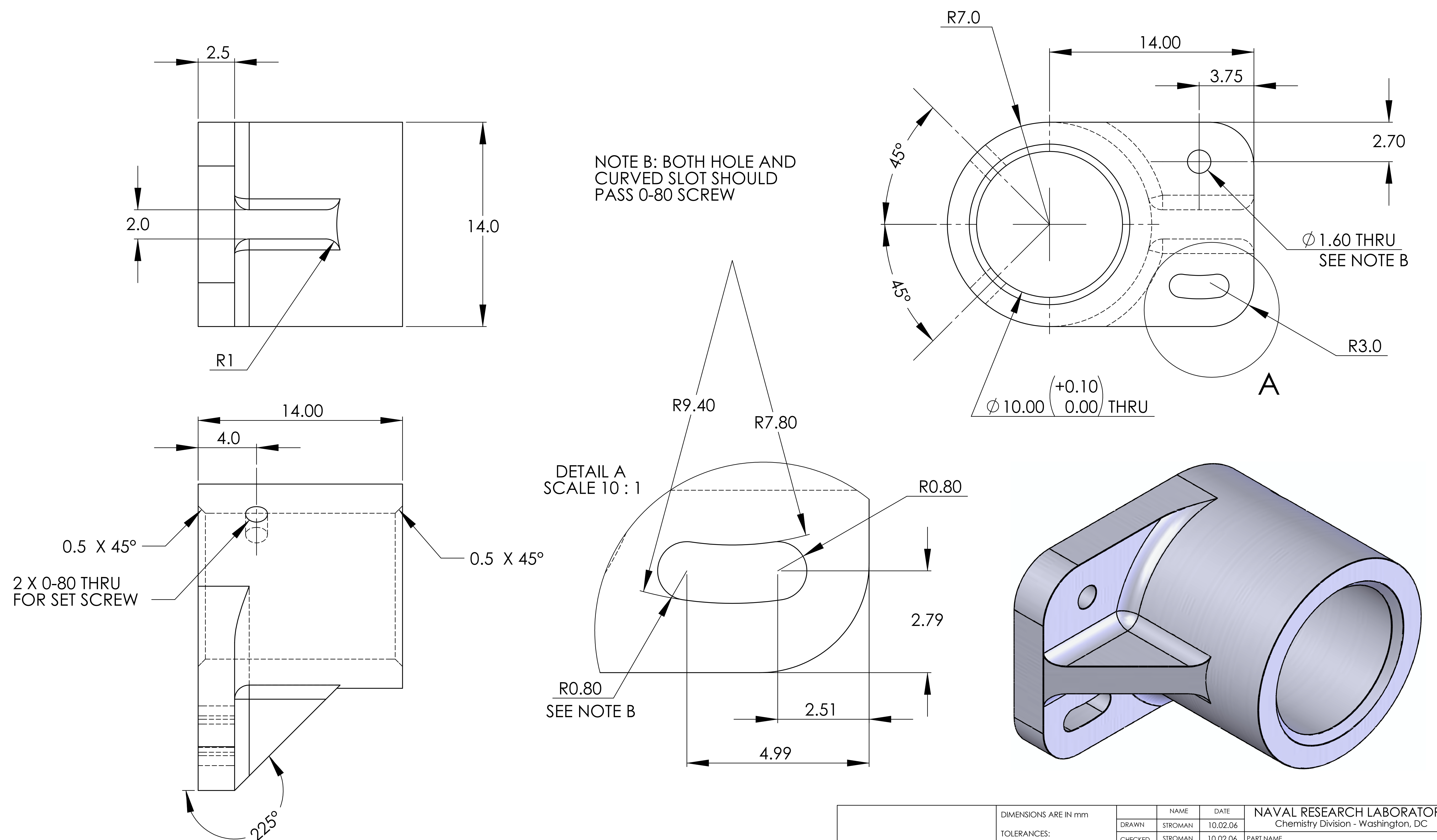
THIS PART MATES TO:
BOSS-P3-1 (ID OF THIS PART SLIPS OVER OD OF BOSS-P3-1, SECURED BY 3 SCREWS)

ALL DIMENSIONS AFTER ANODIZATION

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	09.29.06
	CHECKED	STROMAN	09.29.06
	ENG APPR.	STROMAN	09.29.06
MATERIAL: 6061-T6 Aluminum	PROJECT: DARPA BOSS		
FINISH: GLASS BEAD, HARD COAT ANODIZE (TYPE III) DYED BLACK, TEFLON IMPREGNATED	ASSEMBLY: Prototype III		

NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME	Front Side Cam Constraint
PART NO.	BOSS-P3-11
SIZE	B
DWG. NO.	BOSS-P3-11
REV.	1.0
SCALE	2:1
MASS	4.57g
SHEET	1 OF 1

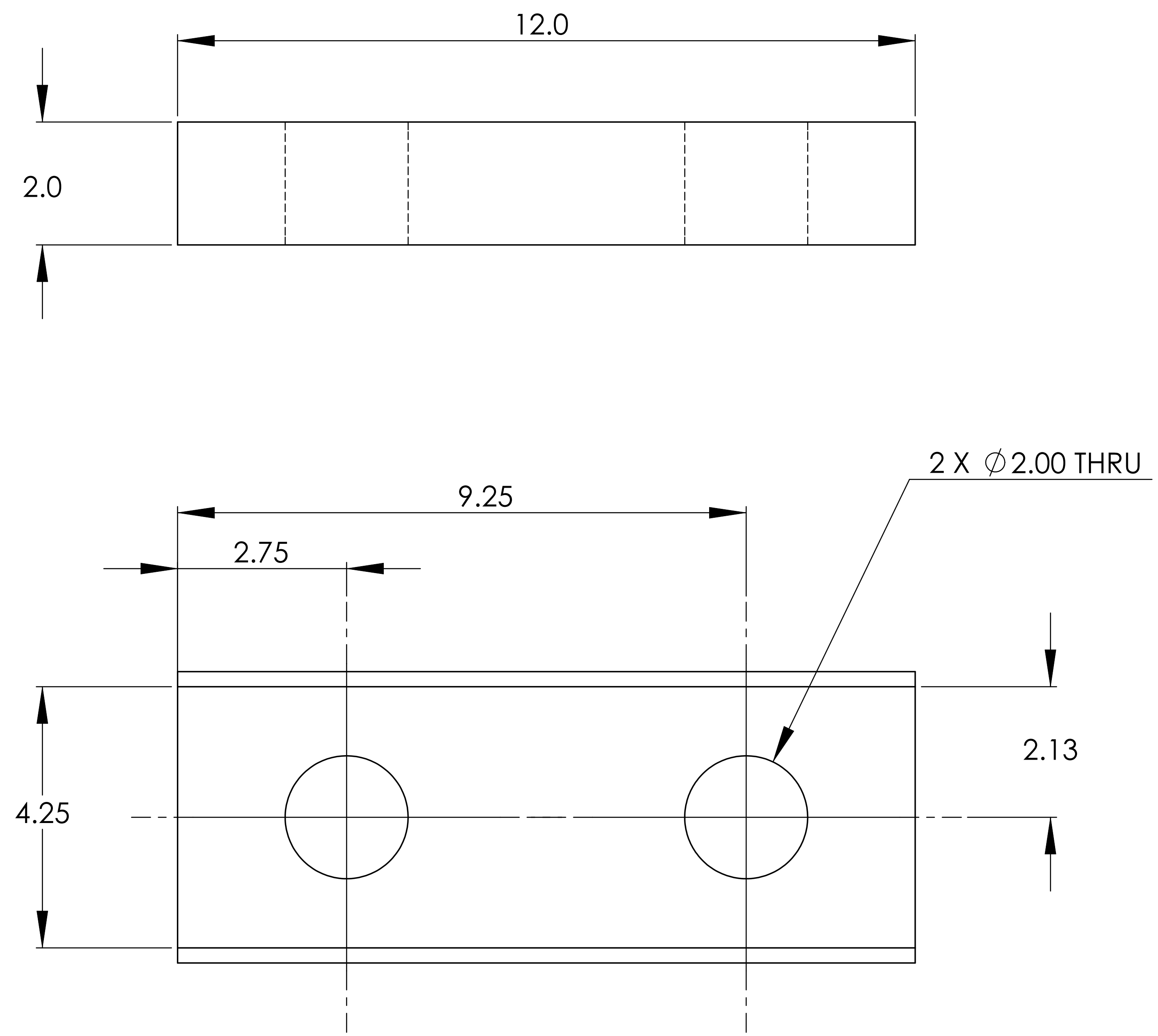


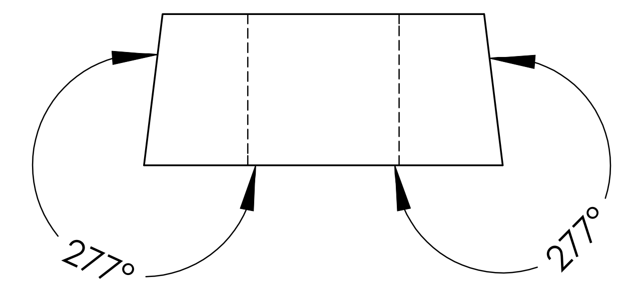
ALL DIMENSIONS AFTER ANODIZATION

THIS PART MATES TO:
BOSS-P3-1 (THIS PART BOLTS ONTO FLANGE ON BOSS-P3-4 WITH 0-80 SCREWS)
BOSS-P3-21 (BOSS-P3-21, STEPPER MOTOR, IS RETAINED IN THIS BRACKET BY TWO SET SCREWS)

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	10.02.06
	CHECKED	STROMAN	10.02.06
	ENG APPR.	STROMAN	10.17.06
MATERIAL 6061-T6 ALUMINUM	PROJECT DARPA BOSS		
FINISH GLASS BEAD, HARD COAT ANODIZE (TYPE III), DYED BLACK	ASSEMBLY Prototype 3		

NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC	
PART NAME	Motor Bracket
PART NO.	BOSS-P3-12
SIZE B	DWG. NO. BOSS-P3-12 — REV. 1.1
SCALE:4:1	MASS: 3.69g — SHEET 1 OF 1





THIS PART MATES TO:
BOSS-P3-4 (PINNED TO THIS PART)

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL: BLACK DELRIN

FINISH

	NAME	DATE
DRAWN	STROMAN	09.29.06
CHECKED	STROMAN	09.29.06
ENG APPR.	STROMAN	09.29.06

PROJECT: DARPA BOSS

ASSEMBLY: Prototype 3

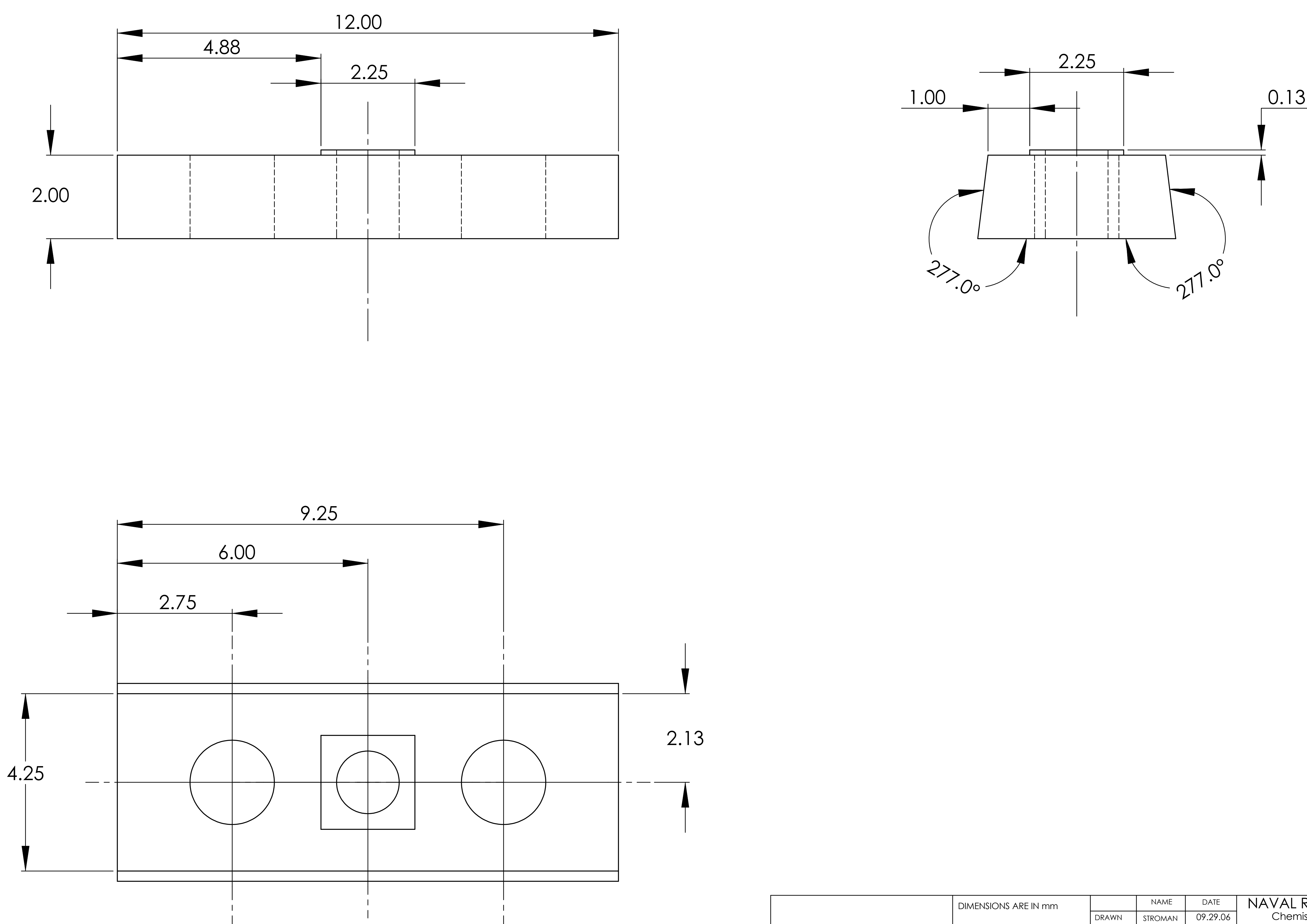
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME: Mount 2 Guide

PART NO.: BOSS-P3-13

SIZE: B | DWG. NO.: BOSS-P3-13 | REV.: 1.0

SCALE:5:1 | MASS: 0.12g | SHEET 1 OF 1



THIS PART MATES TO:
BOSS-P3-4 (PINNED TO THIS PART)

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	09.29.06
	CHECKED	STROMAN	09.29.06
	ENG APPR.	STROMAN	09.29.06
MATERIAL BLACK DELRIN	PROJECT DARPA BOSS		
FINISH	ASSEMBLY Prototype 3		

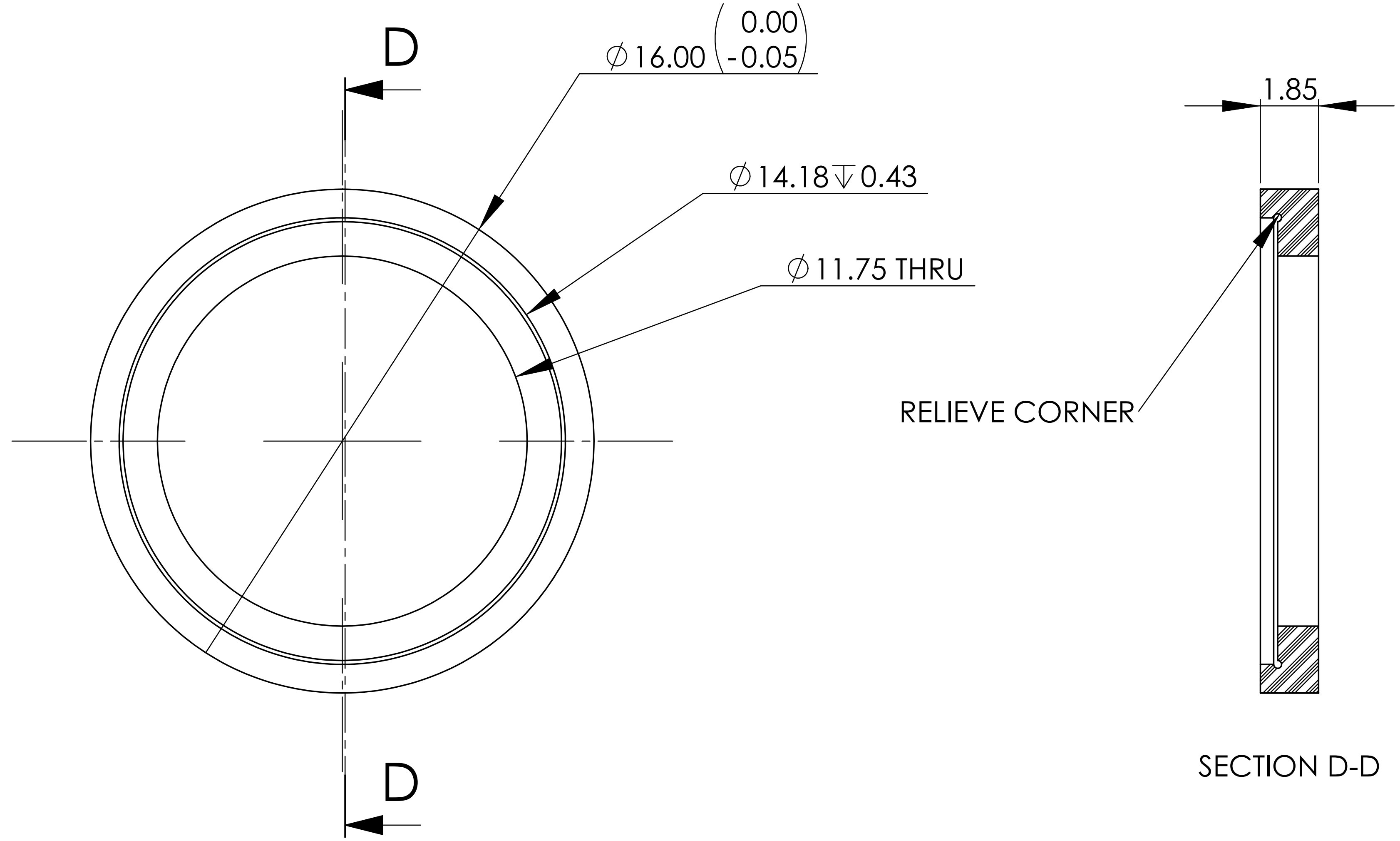
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME: Mount 2 Guide with Bearing

PART NO. BOSS-P3-14

SIZE	DWG. NO.	REV.
B	BOSS-P3-14	1.0

SCALE:10:1 MASS: 0.12g SHEET 1 OF 1



THIS PART MATES TO:
BOSS-P3-8 (THIS PART IS PRESSED INTO BOSS-P3-8 TO RETAIN LENS)

DIMENSIONS ARE IN mm		NAME	DATE
TOLERANCES: ANGULAR: ± 1; ONE PLACE DECIMAL ± 0.1; TWO PLACE DECIMAL ± 0.05	DRAWN	STROMAN	10.02.06
	CHECKED	STROMAN	10.02.06
	ENG APPR.	STROMAN	10.02.06
MATERIAL: BLACK DELRIN	PROJECT: DARPA BOSS		
FINISH	ASSEMBLY: Prototype 3		

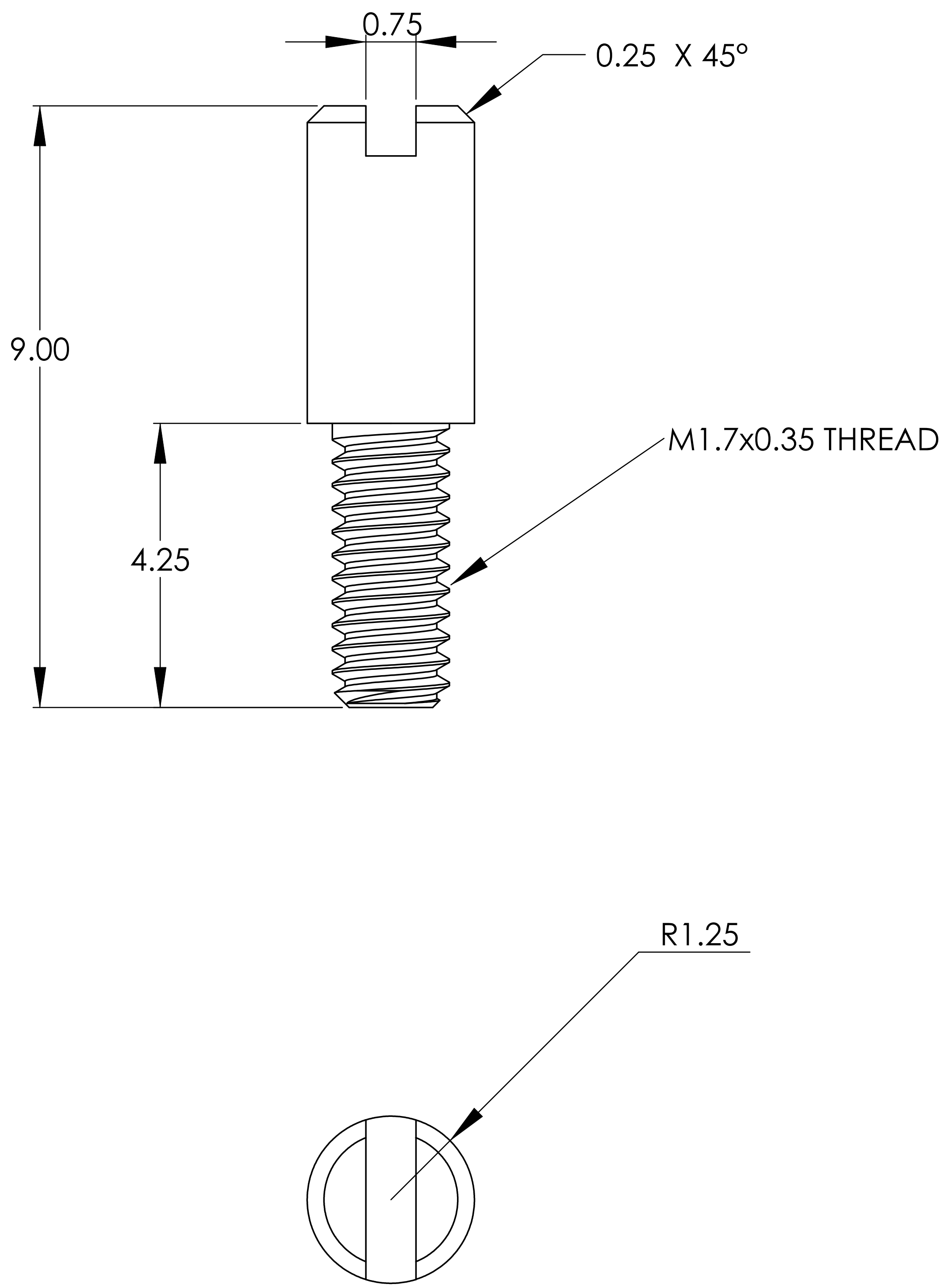
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME: Lens #6 Retaining Ring

PART NO.: BOSS-P3-15

SIZE	DWG. NO.	REV.
B	BOSS-P3-15	1.0

SCALE:5:1 | MASS: 0.20g | SHEET 1 OF 1



THIS PART MATES TO:
BOSS-P3-22 (THIS RING THREADS INTO THE APERTURE)

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL
STEEL

FINISH

	NAME	DATE
DRAWN	STROMAN	10.03.06
CHECKED	STROMAN	10.03.06
ENG APPR.	STROMAN	10.03.06

PROJECT
DARPA BOSS

ASSEMBLY
Prototype 3

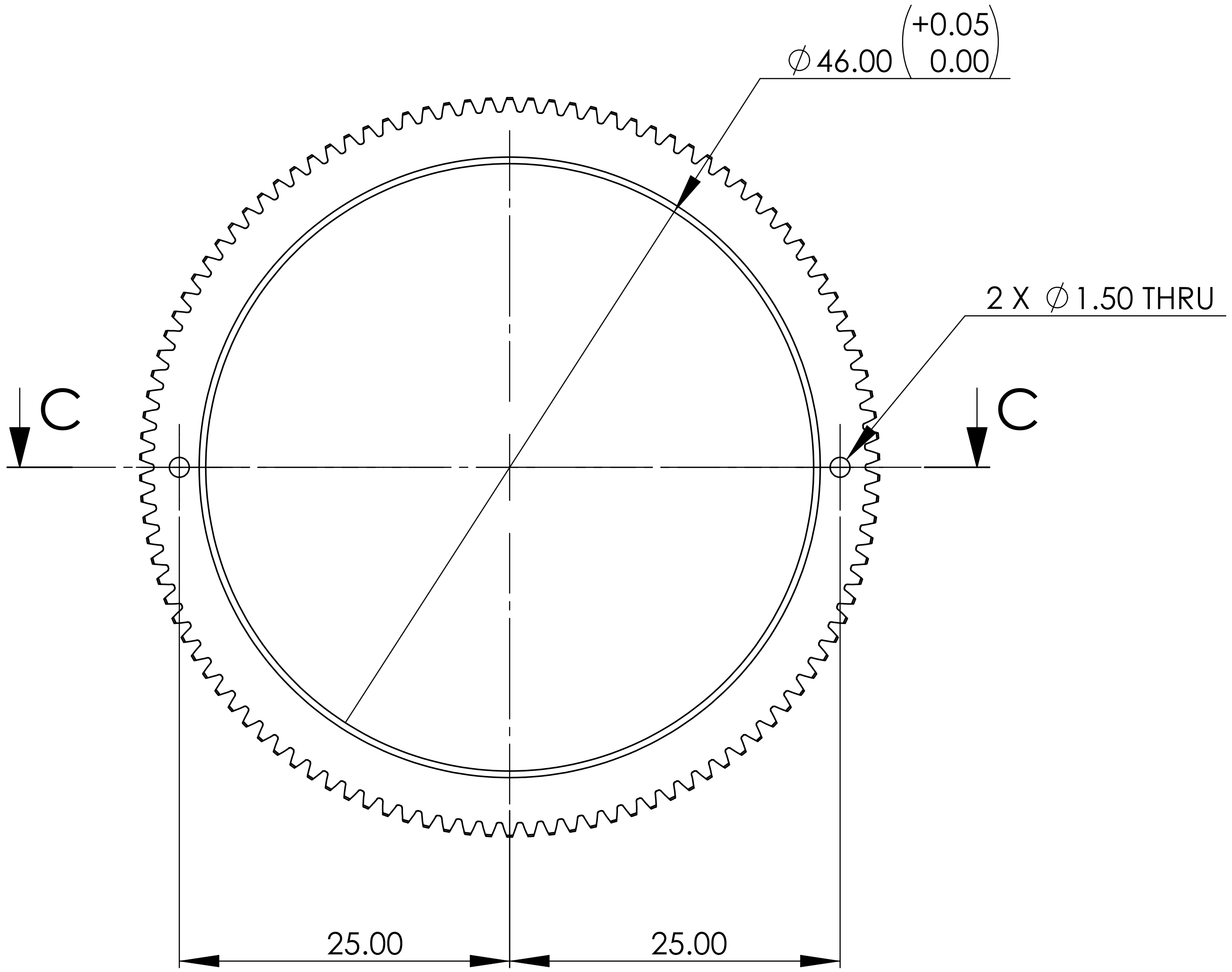
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME
Aperture Pin

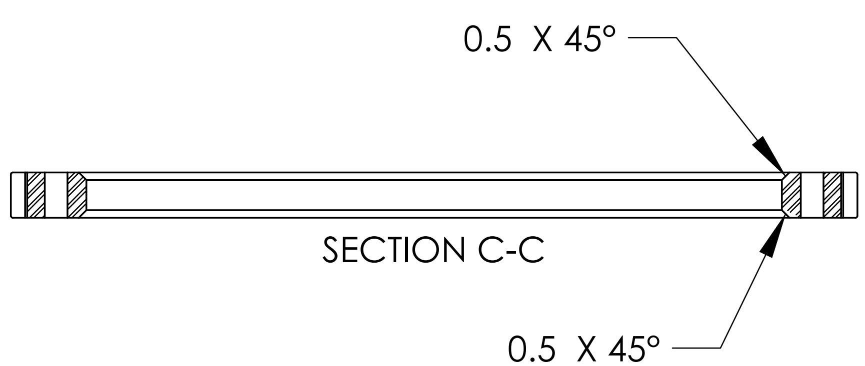
PART NO.
BOSS-P3-16

SIZE B | DWG. NO. BOSS-P3-16 | REV. 1.0

SCALE:10:1 | MASS: 0.23g | SHEET 1 OF 1



THIS PART IS A MODIFIED PART, ORIGINALLY SDP-SI P/N: S12N05M110A0310
THE MODIFICATIONS ARE (1) INCREASE BORE AND (2) ADD HOLES FOR PINS



SECTION C-C

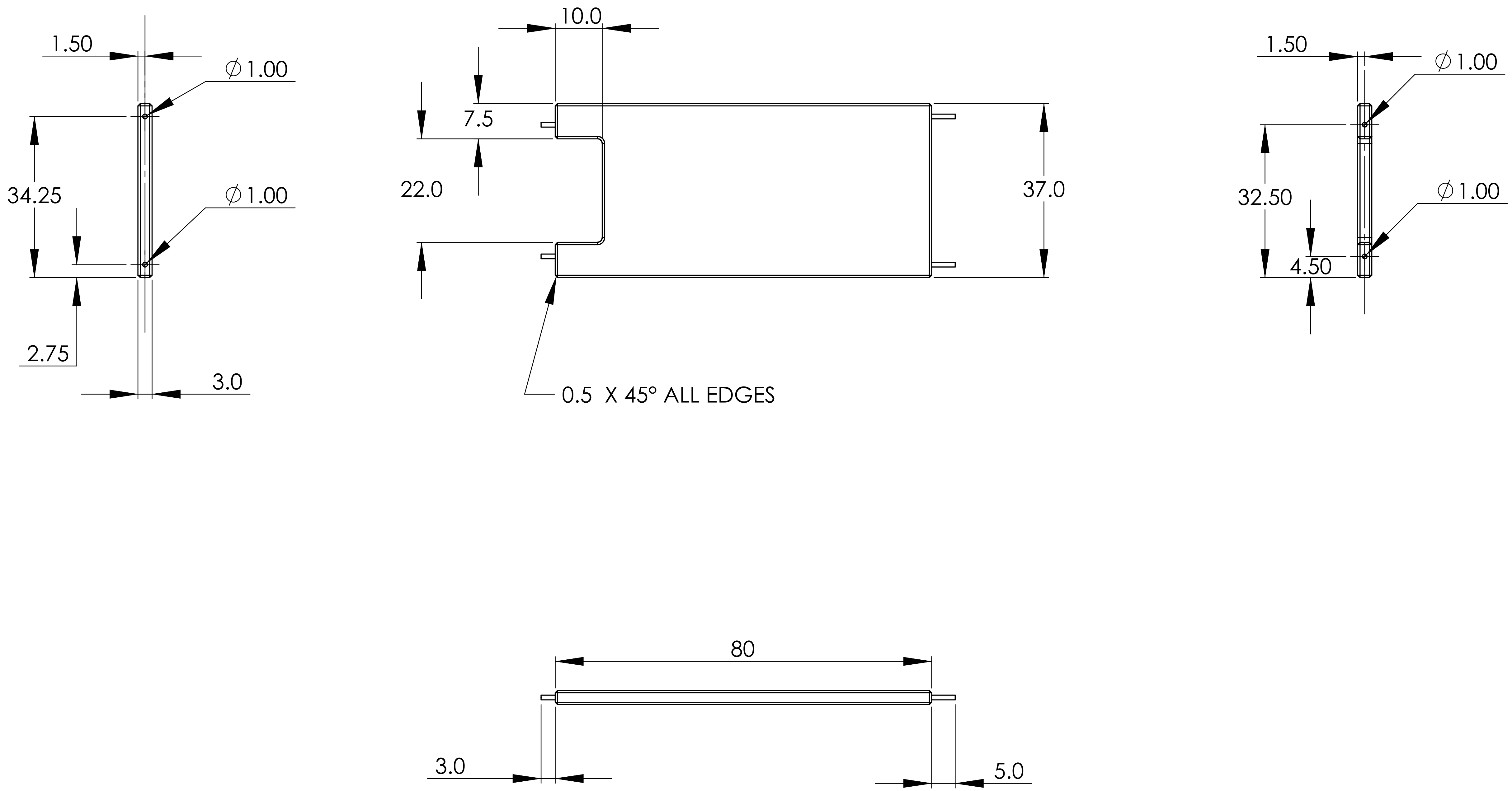
	NAME	DATE	NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC
DRAWN	STROMAN	10.09.06	
CHECKED	STROMAN	10.09.06	PART NAME: SDP-SI Spur Gear
ENG APPR.	STROMAN	10.09.06	
PROJECT: DARPA BOSS			PART NO.: BOSS-P3-17
ASSEMBLY: Prototype 3			SIZE: B · DWG. NO.: BOSS-P3-17 · REV.: 1.0
			SCALE:2:1 · MASS: 5.84g · SHEET 1 OF 1

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL: 2024 ALUMINUM

FINISH



FABRICATE ALUMINUM WRENCH BODY,
THEN INSERT STEEL 1.00mm DIA PINS

BREAK ALL EDGES 0.010 IN, TUMBLE DEBURR

DIMENSIONS ARE IN mm		NAME	DATE
TOLERANCES:	DRAWN	STROMAN	10.03.06
ANGULAR: ± 1	CHECKED	STROMAN	10.03.06
ONE PLACE DECIMAL ± 0.1	ENG APPR.	STROMAN	10.03.06
TWO PLACE DECIMAL ± 0.05	PROJECT: DARPA BOSS		
MATERIAL: ALUMINUM AND STEEL			
FINISH	ASSEMBLY: Prototype 3		

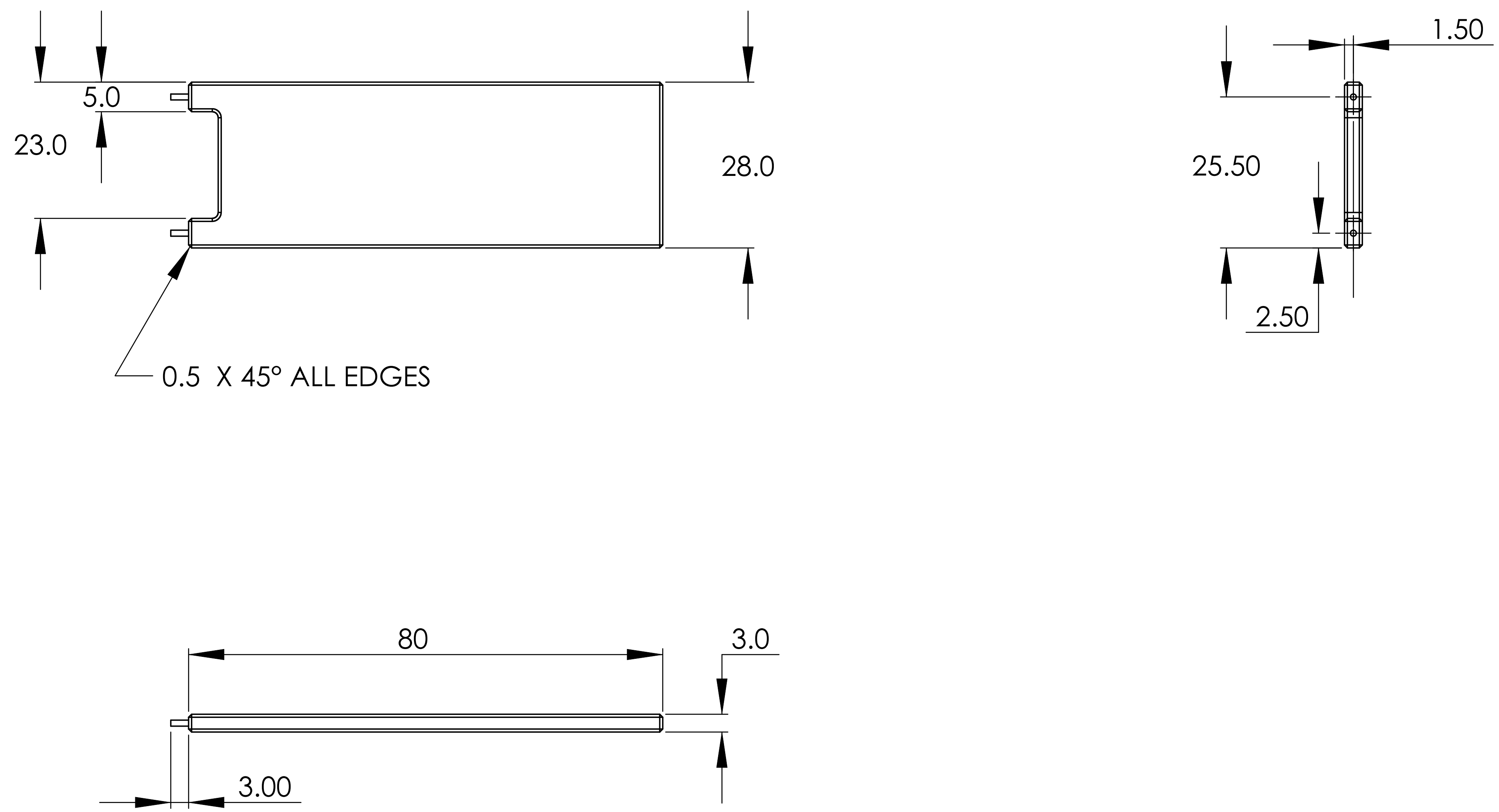
NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME: Spanner Wrench for Lenses 1,2,3

PART NO.: BOSS-P3-18

SIZE: B | DWG. NO.: BOSS-P3-18 | REV.: 1.0

SCALE:1:1 | MASS: 22.06g | SHEET 1 OF 1



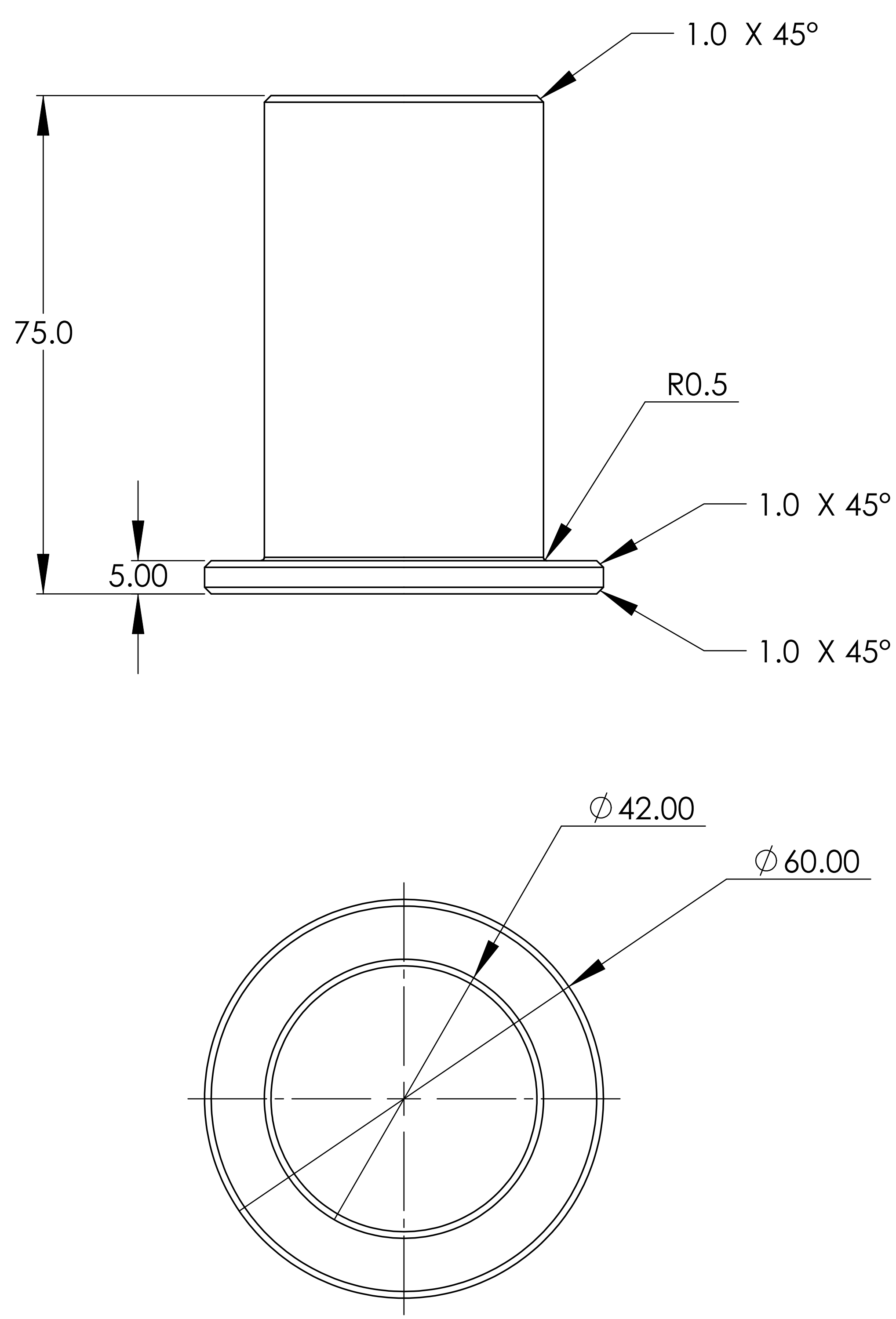
FABRICATE ALUMINUM WRENCH BODY,
THEN INSERT STEEL 1.00mm DIA PINS

BREAK ALL EDGES 0.010 IN, TUMBLE DEBURR

DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	10.03.06
	CHECKED	STROMAN	10.03.06
	ENG APPR.	STROMAN	10.03.06
MATERIAL ALUMINUM AND STEEL	PROJECT DARPA BOSS		
FINISH	ASSEMBLY Prototype 3		

NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

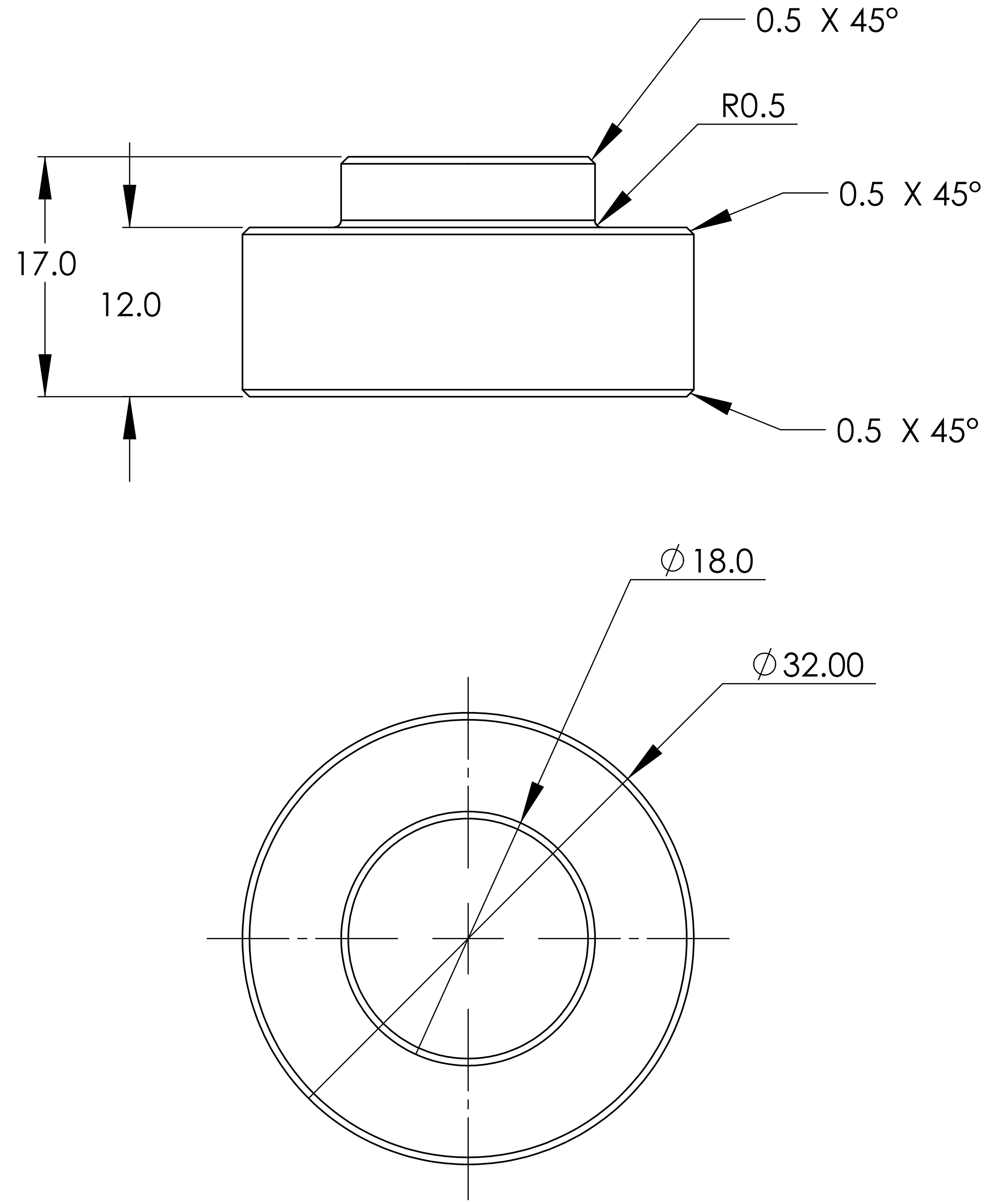
PART NAME	Spanner Wrench for Lenses 4 and 5		
PART NO.	BOSS-P3-19		
SIZE B	DWG. NO. BOSS-P3-19		REV. 1.0
SCALE:1:1	MASS: 17.28g		SHEET 1 OF 1



ALL DIMENSIONS AFTER ANODIZATION

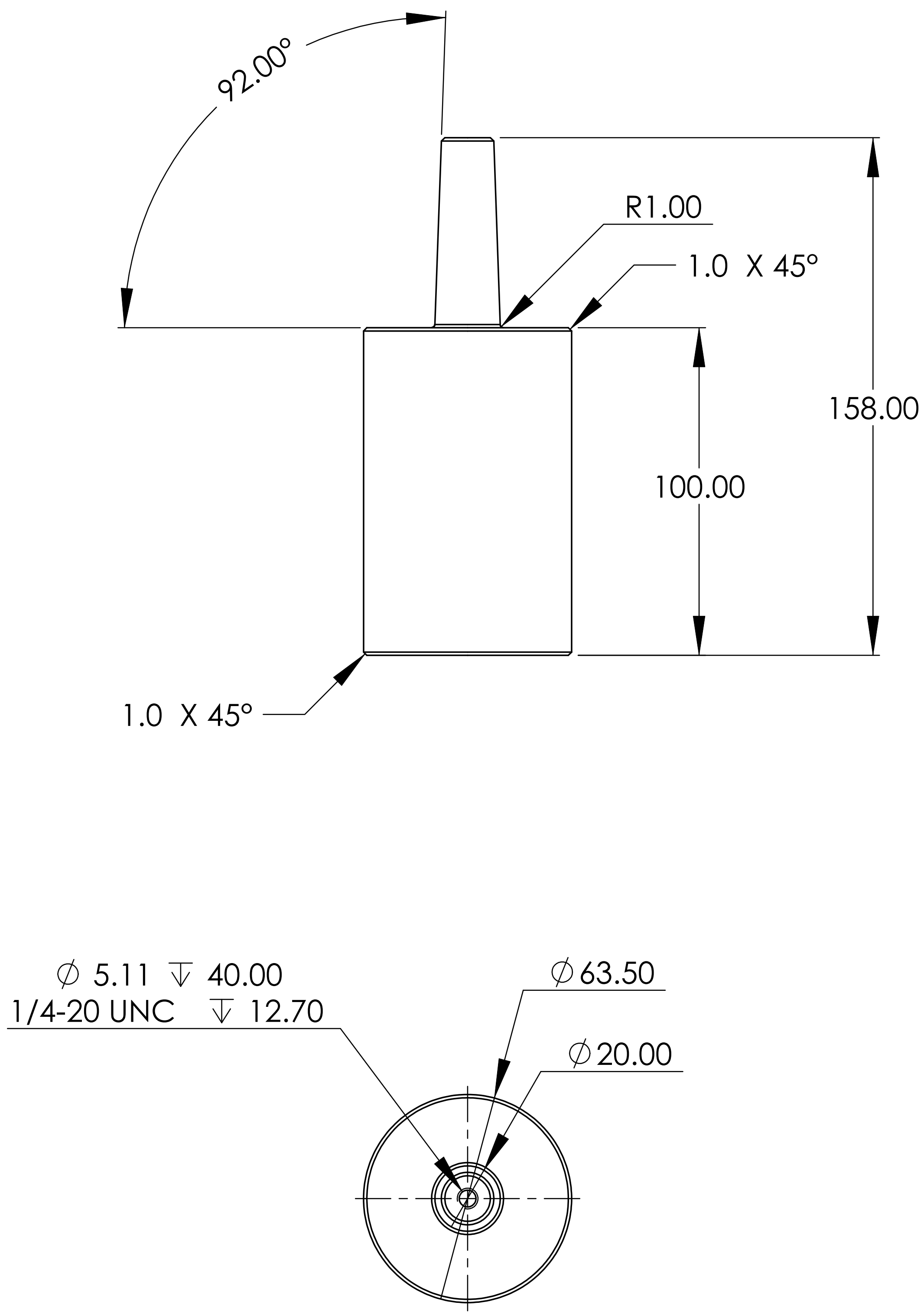
DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE
	DRAWN	STROMAN	10.03.06
	CHECKED	STROMAN	10.03.06
	ENG APPR.	STROMAN	10.03.06
MATERIAL 6061-T6 ALUMINUM	PROJECT DARPA BOSS		
FINISH HARD COAT ANODIZE (TYPE III), DYED BLACK, TEFLON IMPREGNATED	ASSEMBLY Prototype 3		

NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC		
PART NAME Cam Assembly Mandrel		
PART NO. BOSS-P3-20		
SIZE B	DWG. NO. BOSS-P3-20	REV. 1.0
SCALE:1:1	MASS: 299.36g	SHEET 1 OF 1

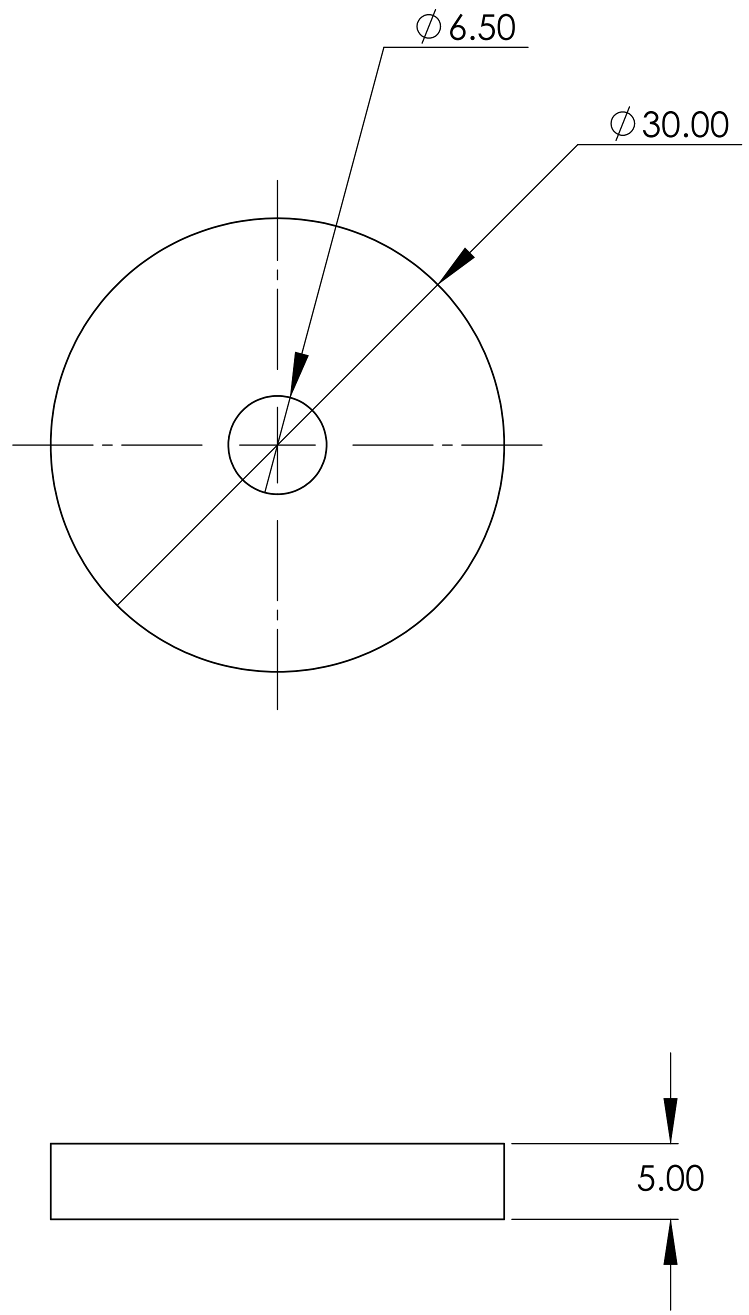


ALL DIMENSIONS AFTER ANODIZATION

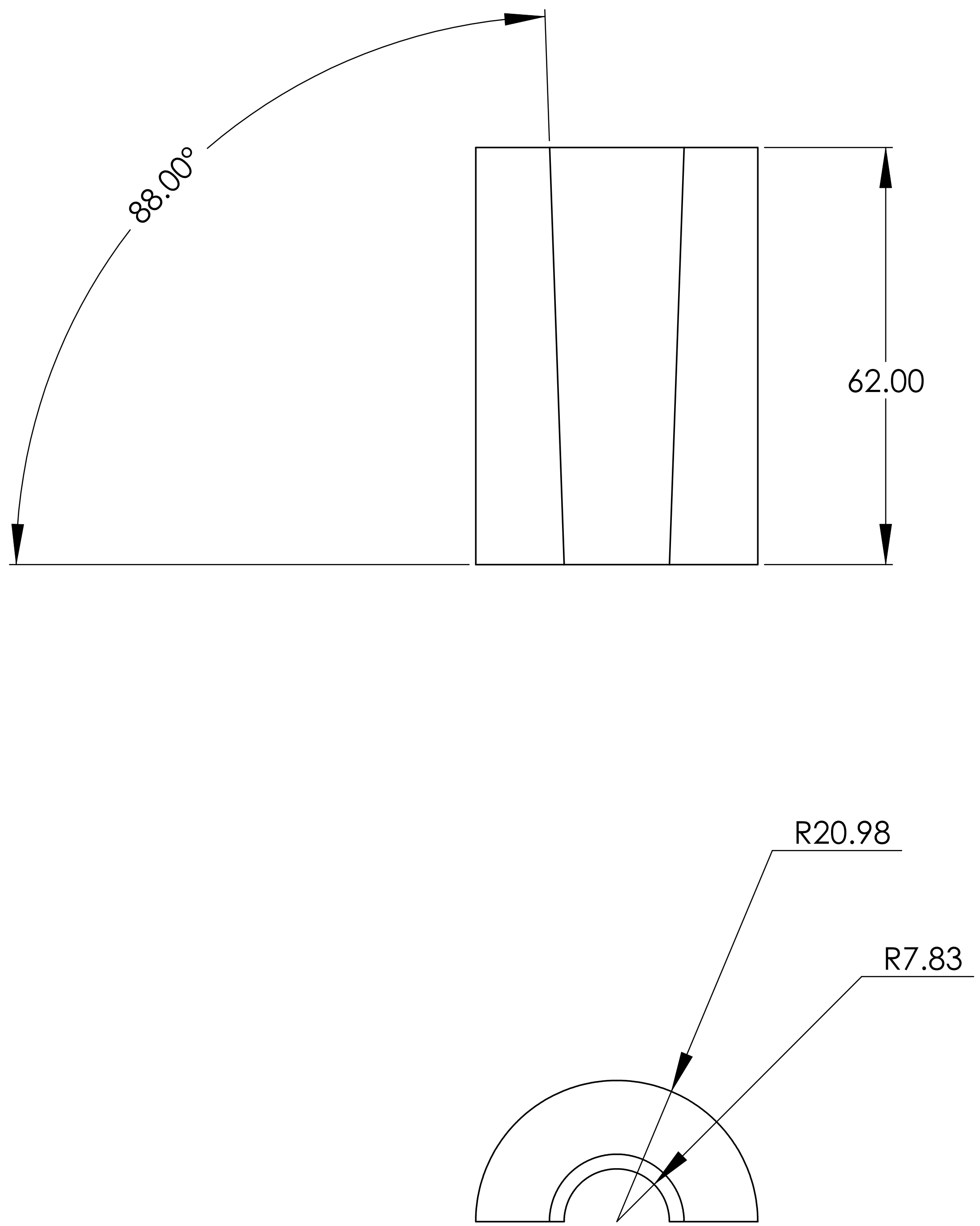
DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05	NAME / DATE DRAWN: STROMAN 10.03.06 CHECKED: STROMAN 10.03.06 ENG APPR.: STROMAN 10.03.06	NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC	
MATERIAL: 6061-T6 Aluminum	PROJECT: DARPA BOSS	PART NAME: Lens #1 Plug for Pin Insertion	
FINISH: HARD COAT ANODIZE (TYPE III), DYED BLACK, TEFLON IMPREGNATED	ASSEMBLY: Prototype 3	PART NO.: BOSS-P3-21	
		SIZE: B / DWG. NO.: BOSS-P3-21	REV.: 1.0
		SCALE:2:1 / MASS: 29.42g	SHEET 1 OF 1



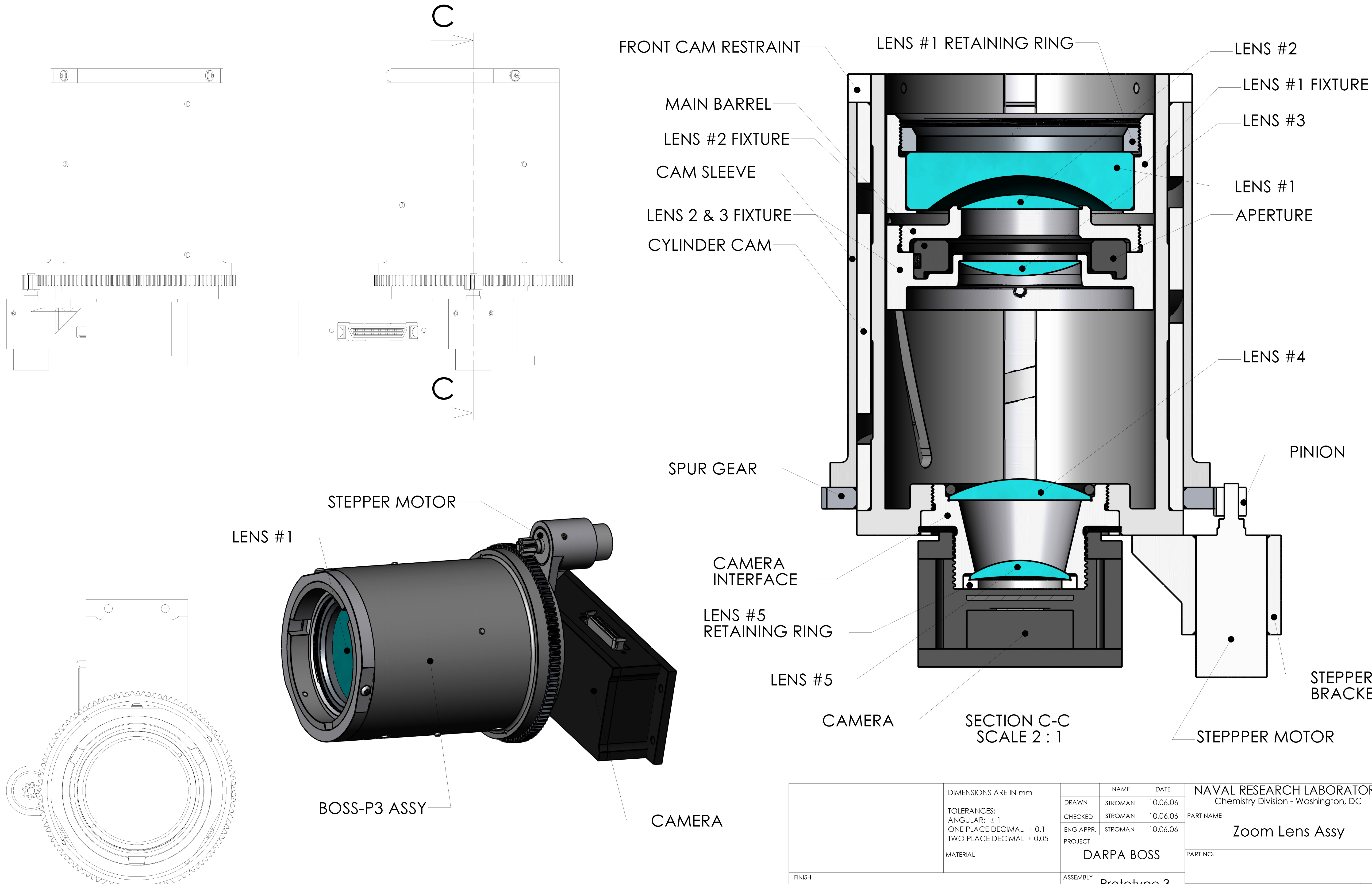
DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE	NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC
	DRAWN	STROMAN	10.03.06	
	CHECKED	STROMAN	10.03.06	PART NAME Split Cylinder Fixture
	ENG APPR.	STROMAN	10.03.06	
MATERIAL ALUMINUM	PROJECT DARPA BOSS			PART NO. BOSS-P3-22
FINISH	ASSEMBLY Prototype 3			SIZE B DWG. NO. BOSS-P3-22 REV. 1.0
				SCALE:1:2 MASS: SHEET 1 OF 1



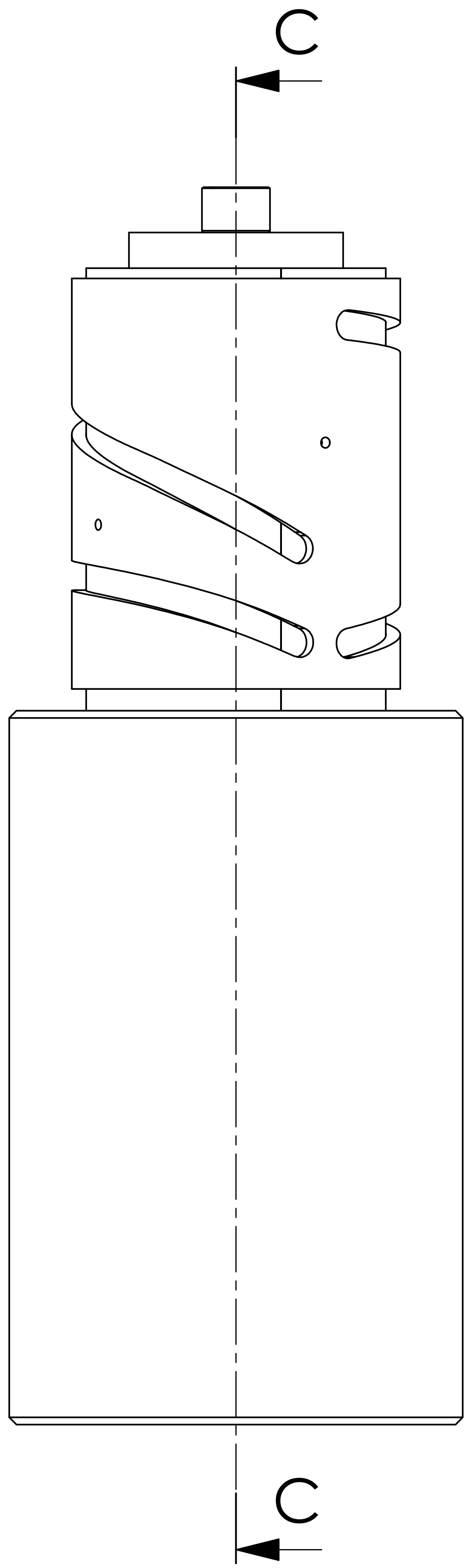
DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE	NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC	
	DRAWN	STROMAN	10.03.06		
	CHECKED	STROMAN	10.03.06	PART NAME Split Cylinder Plate	
	ENG APPR.	STROMAN	10.03.06		
MATERIAL ALUMINUM	PROJECT DARPA BOSS			PART NO. BOSS-P3-23	
FINISH	ASSEMBLY Prototype 3			SIZE B | DWG. NO. BOSS-P3-23	REV. 1.0
				SCALE:2:1 | MASS:	SHEET 1 OF 1

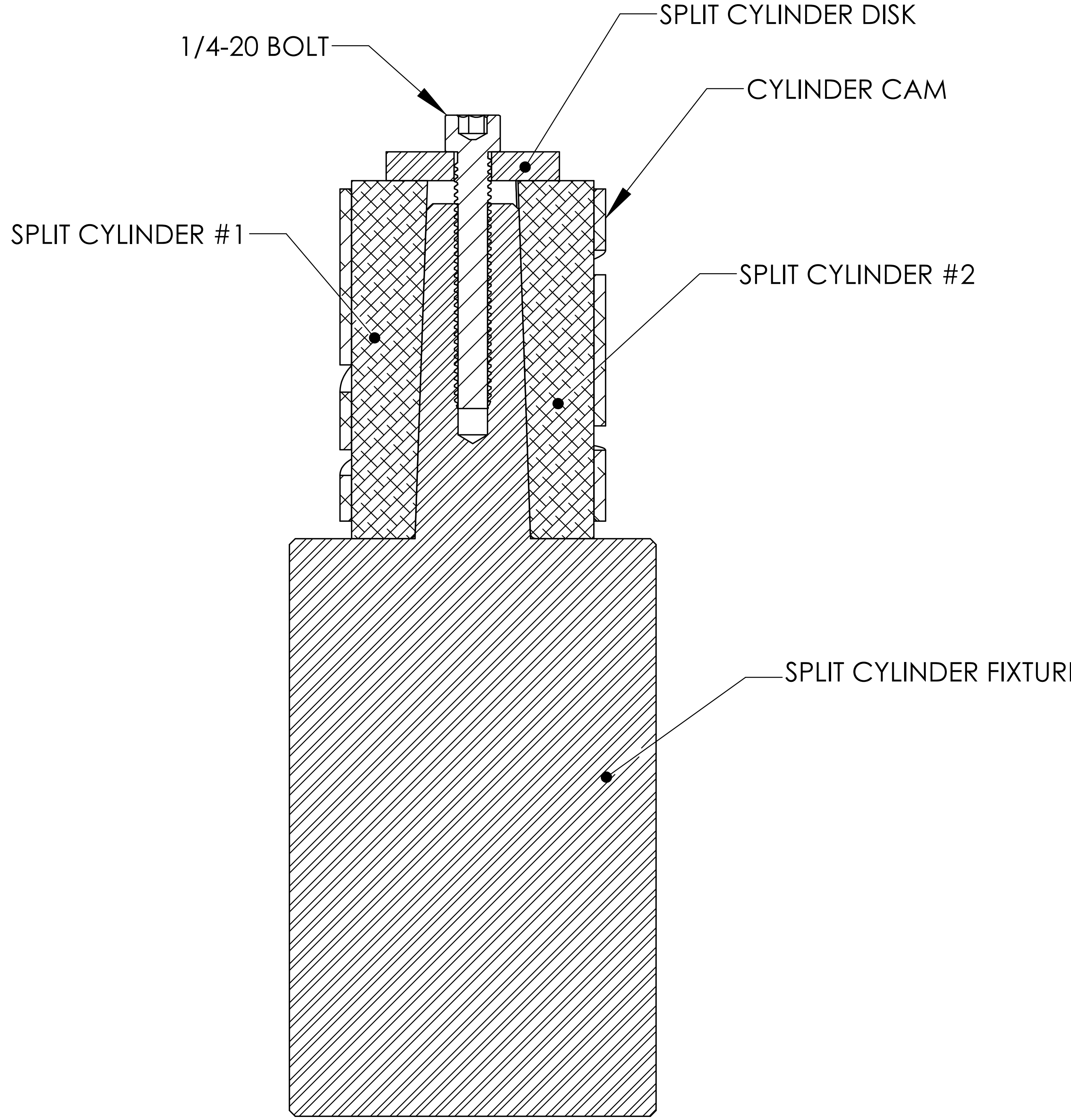


DIMENSIONS ARE IN mm		NAME	DATE	NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC
TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05	DRAWN	STROMAN	10.03.06	PART NAME Split Cylinder
	CHECKED	STROMAN	10.03.06	
	ENG APPR.	STROMAN	10.03.06	
MATERIAL ALUMINUM	PROJECT DARPA BOSS			PART NO. BOSS-P3-24
FINISH	ASSEMBLY Prototype 3			SIZE B DWG. NO. BOSS-P3-24 REV. 1.0
				SCALE:1:1 MASS: SHEET 1 OF 1



DIMENSIONS ARE IN mm TOLERANCES: ANGULAR: ± 1 ONE PLACE DECIMAL ± 0.1 TWO PLACE DECIMAL ± 0.05		NAME	DATE	NAVAL RESEARCH LABORATORY Chemistry Division - Washington, DC
	DRAWN	STROMAN	10.06.06	PART NAME
	CHECKED	STROMAN	10.06.06	Zoom Lens Assy
	ENG APPR.	STROMAN	10.06.06	
MATERIAL	PROJECT DARPA BOSS			PART NO.
FINISH	ASSEMBLY Prototype 3			SIZE B · DWG. NO. BOSS-P3-25 · REV. 1.0
				SCALE:1:1 · MASS: · SHEET 1 OF 1





SECTION C-C

TIGHTENING THE BOLT PUSHES THE TWO CYLINDER HALVES APART, STRESSING THE CAM SO THAT IT DOES NOT WARP WHEN THE SLOTS ARE CUT. THIS ALSO PROVIDES A WAY TO HOLD THE CAM WHEN MACHINING THE SLOTS.

DIMENSIONS ARE IN mm

TOLERANCES:
ANGULAR: ± 1
ONE PLACE DECIMAL ± 0.1
TWO PLACE DECIMAL ± 0.05

MATERIAL

FINISH

	NAME	DATE
DRAWN	STROMAN	10.06.06
CHECKED	STROMAN	10.06.06
ENG APPR.	STROMAN	10.06.06

PROJECT
DARPA BOSS

ASSEMBLY
Prototype 3

NAVAL RESEARCH LABORATORY
Chemistry Division - Washington, DC

PART NAME
Split Cylinder Assy

PART NO.

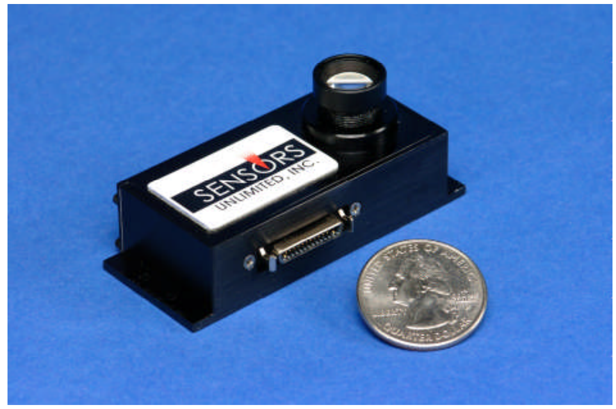
SIZE B | DWG. NO. BOSS-P3-26 | REV. 1.0

SCALE:1:1 | MASS: | SHEET 1 OF 1

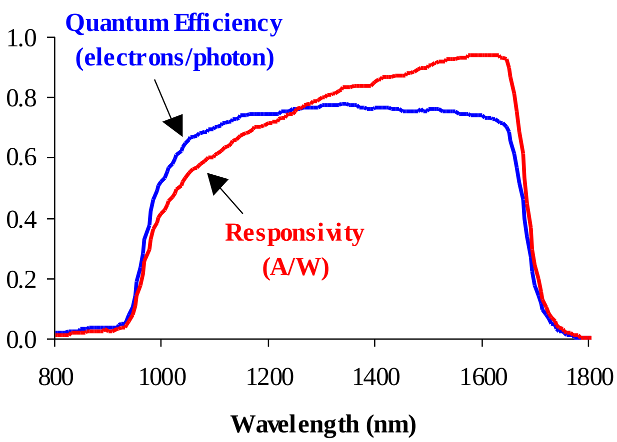
Component Specification Sheets

SU320US-1.7RT
InGaAs NIR Snapshot MicroCamera

The SU320US-1.7RT is the smallest SWIR camera available. This high resolution, room temperature video camera allows users to capture images from pulsed laser and moving events with unparalleled linearity and sensitivity, connecting to PCs with the Camera Link® interface. The small size and low power allow the camera to placed anywhere easily.



APPLICATIONS
- Unmanned Aerial Vehicles
- Covert Surveillance
- Machine Vision
- Inspection of Fiberoptic Components
- Free Space Communications



FEATURES
- High sensitivity in the near infrared spectrum (900 nm to 1700 nm)
- Factory set Non-Uniformity Corrections (NUCs)
- Compact size < 26 cm^3
- Low power < 1.2 W
- All solid-state InGaAs imager
- Digital & analog outputs
- Camera Link® compatible
- Room temperature operation
- Accepts standard C-mount lenses or M12x0.5 thread miniature lenses

Designed for imaging in the short wave infrared (900 nm to 1700 nm) on unmanned aerial vehicles and robots, the SU320US-1.7RT Indium Gallium Arsenide camera delivers high resolution image quality with high linearity to standard monitors or frame grabbers. The SU320US-1.7RT utilizes Sensors Unlimited's proprietary snapshot exposure focal plane array, which features a 320 x 256 pixel matrix of 25 μm square pixels. Imaging options include interlaced or progressive scan, RS-170 or CCIR video output, automatic gain control and windowed operation. Like all SUI™ high performance InGaAs cameras, the SU320US operates the FPA at room temperature, while consuming less than 1.6 W. The 12 bit digital data is also available simultaneously in Camera Link™ format. The SU320US-1.7RT is compatible with most commercially available video and digital frame grabber boards.

3490 U.S. Route 1 • Princeton, New Jersey 08540
Phone: (609) 520-0610 • Fax: (609) 520-0638
www.sensorsinc.com • info@sensorsinc.com

MECHANICAL

Length x Width x Height	6 cm x 2.8 cm x 1.7 cm
Weight	< 70 g (with lens)
Focal Plane Array Format	320 x 256 pixels
Pixel Pitch	25 μm
Lens Mount	C-mount or M12x0.5 thread

ENVIRONMENTAL & POWER

Operating Temperature	5°C to 35°C
Storage Temperature	-10°C to 60°C
Humidity	Non-condensing
Power Requirements: AC Adapter Supplied DC (Voltage/Current)	 100-240 VAC, 47-63 Hz 6-16 V/ 1.2W at 25°C ambient

ELECTRICAL SPECIFICATIONS

Optical Fill Factor	> 99.9%
Spectral Response	900 nm to 1700 nm
Quantum Efficiency	> 70% from 1000 nm to 1600 nm
Mean Detectivity, D*[1]	> 8 x 10^{12} cm√Hz/W
Noise Equivalent Irradiance[1]	< 2 x 10^{9} photons/cm^2/s
Noise (RMS)[1]	< 200 electrons
Full Well Capacity[1]	> 3 x 10^{5} electrons
True Dynamic Range	> 2000:1
Operability[2]	> 99%
Operation Settings	Seven settings with a 16.3 ms exposure time and a range of gains.
Image Correction	2-point (offset and gain) pixel by pixel for each operation setting, bad pixel substitution
Digital Output Format	12 bit Camera Link® (corrected and uncorrected data is available)
Analog Output Format	Interlaced or progressive scan
Frame Rate	60 Hz RS170 progressive scan 50 Hz CCIR progressive scan
Scan Mode	Continuous or triggered

[1] λ =1550 nm, exposure time = 16.3 ms (no lens), highest gain setting.
[2] The fraction of pixels with responsivity deviation less than 30% from the mean.

Stepper Motors

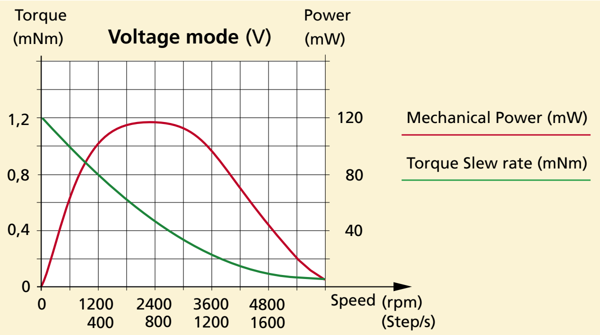
Two phases, 20 steps per revolution

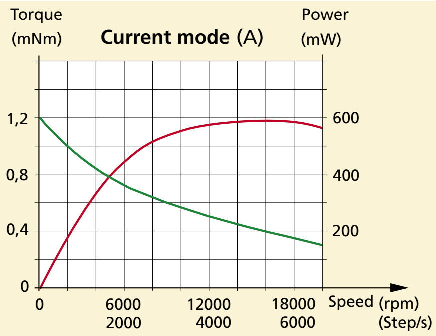
For combination with:
Gearheads: 10/1, 12/3, 12/5
Encoders: AE 30B19
Drive Electronics: AD VL M, AD VM M, AD CM M

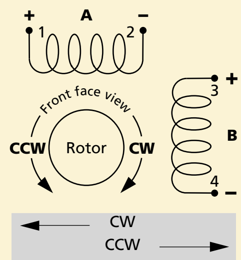
Series AM 1020

		V 3	V 6	V 12	A 0,25	
		Voltage mode			Current mode	
1	Nominal voltage U_N	3	6	12		V DC
2	Phase resistance (at 20°C)	16	65	250	7,4	Ω
3	Phase inductance (1kHz)	4,5	18	70	2,1	mH
4	Nominal current per phase (both phases ON)	0,175	0,09	0,045	0,25	A
5	Back-EMF amplitude	2,25	4,5	9	1,5	V/k step/s
6	Holding torque [1] (at nominal current in both phases)	1,6				mNm
7	Holding torque [1] (at twice the nominal current)	2,4				mNm
8	Residual and friction torque	0,25				mNm
9	Thermal resistance winding-ambient air	73				°C/W
10	Winding temperature tolerated, max.	130				°C
11	Ambient temperature range	–35 ... +70				°C
12	Thermal time constant	90				s
13	Step angle (full step)	18				degree
14	Angular accuracy [2]	± 10				% of full step
15	Rotor inertia	9				$\cdot 10^{-9}$ kgm²
16	Shaft bearings	sintered bronze sleeves	ball bearings, preloaded			
17	Shaft load, max.:	(standard)	(optional)			
	– radial (3 mm from bearing)	0,3	4,0			N
	– axial	0,3	2,0			N
18	Shaft play, max.:					
	– radial (0,2N)	15	12			µm
	– axial (0,2N)	150	~0			µm
19	Weight	5,5				g
20	Isolation test voltage	200				V
21	Resonance frequency	140				Hz
22	Electrical time constant	0,28				ms

[1] with bipolar driver
[2] 2 phases ON, balanced phase current

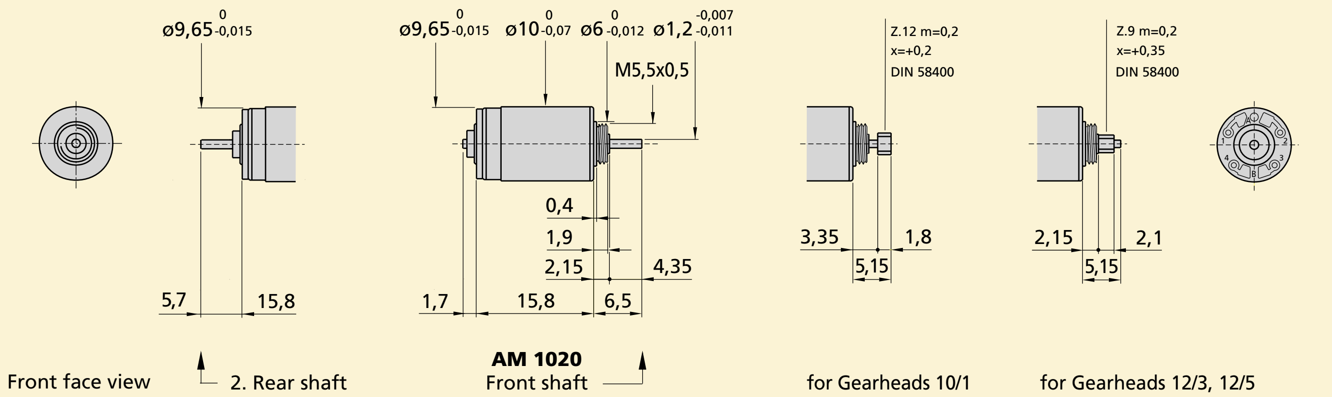






	1	2	3	4
Phase **A**	+	–	–	+
Phase **B**	+	+	–	–

Torque/Speed curves measured with a load inertia of 10 $\cdot 10^{-9}$ kgm²



Front face view
2. Rear shaft
AM 1020
Front shaft
for Gearheads 10/1
for Gearheads 12/3, 12/5

ARSAPE

Planetary Gearheads

0,1 Nm

For combination with:
Stepper motors: AM 1020

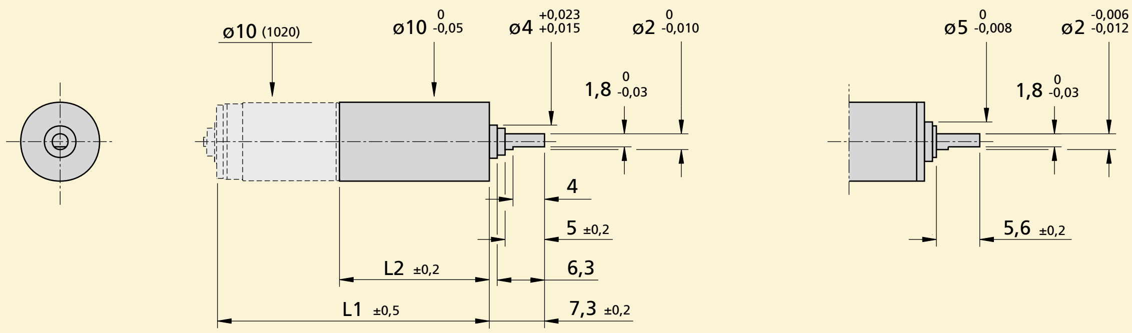
Series 10/1

	10/1	10/1 K
Housing material	metal	metal
Geartrain material	all steel	all steel
Recommended max. input speed for:		
– continuous operation	5000 rpm	5000 rpm
Backlash, at no-load	≤ 3°	≤ 3°
Bearings on output shaft	sintered sleeve bearings	preloaded ball bearings
Shaft load, max.:		
– radial (5 mm from mounting face)	≤ 1 N	≤ 7 N
– axial	≤ 2 N	≤ 5 N [1)]
Shaft press fit force, max.	≤ 10 N	≤ 5 N [1)]
Shaft play (on bearing output):		
– radial	≤ 0,03 mm	≤ 0,02 mm
– axial	≤ 0,10 mm	= 0 mm [1)]
Operating temperature range	– 30 ... + 100 °C	– 30 ... + 100 °C

Specifications

reduction ratio	weight without motor g	length without motor L2 mm	length with motor AM 1020 L1 mm	output torque continuous operation M max. mNm	output torque intermittent operation M max. mNm	direction of rotation (reversible)	efficiency %
4 :1	6	9,7	25,5	5	200	=	90
16 :1	7	12,8	28,6	15	200	=	80
64 :1	8	15,9	31,7	54	200	=	70
256 :1	10	19,0	34,8	100	200	=	60
1 024 :1	11	22,1	37,9	100	200	=	55
4 096 :1	13	25,2	41,0	100	200	=	48

[1)] Limited by the preloaded ball bearings.
A higher axial load negates the preload.



10/1 **10/1 K**